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UNIVERSITI TEKNOLOGI PETRONAS

Biological Treatment of Pharmaceutical Wastewater

**By
Welly Herumurti**

**A THESIS
SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME
AS A REQUIREMENT FOR THE
DEGREE OF MASTER OF SCIENCE
IN CIVIL ENGINEERING**

**BANDAR SERI ISKANDAR
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MALAYSIA**

JULY, 2009

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Teknologi PETRONAS or other institutions.

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I would like to dedicate this to my mother, my father and my sister.

ABSTRACT

The biological wastewater treatment study was performed to treat non-penicillin pharmaceutical wastewater. The study was conducted in two phases. The Phase I focussed on a preliminary study to determine the feasibility of biological treatment for treating pharmaceutical wastewater. The biological treatment in Phase I consisted of two treatment trains; Train 1 which consisted of a semi-anaerobic baffle reactor (SABR) followed by an activated sludge process (ASP) reactor while Train 2 consisted of only an ASP reactor. The Phase II was carried out on anaerobic treatment processes. Anaerobic biological treatment of pharmaceutical wastewater was performed using upflow anaerobic sludge blanket (UASB) and hybrid upflow anaerobic sludge blanket (HUASB) reactors. The UASB and HUASB reactors were operated under mesophilic ($35\pm 2^{\circ}\text{C}$) and thermophilic ($55\pm 2^{\circ}\text{C}$) conditions. Four hydraulic retention times (HRTs) i.e., five, four, three and two days were applied for all reactors. The sludge from an aerobic sewage treatment plant was used as seed biomass in all reactors.

In Phase I, the reactors were fed with influent chemical oxygen demand (COD) concentration of 607-1953 mg/L. Train 1 (SABR-ASP reactor) achieved higher COD removal in treating high strength wastewater (COD 1953 mg/L); however, Train 2 (ASP reactor) achieved higher COD removal in treating low strength wastewater (COD 635 mg/L). The aerobic biomass from a sewage treatment plant was successfully used as seed biomass in aerobic and semi-anaerobic reactors in treating non-penicillin pharmaceutical wastewater.

In Phase II, the reactors were fed with low strength influent (COD 458-526 mg/L) and high strength influent (COD 1770-2217 mg/L). The reactors obtained higher COD removals in treating high strength wastewater. The results show that the reactor performance was significantly affected by type of reactor, HRT and temperature. Both mesophilic UASB and HUASB reactors obtained higher COD and biochemical oxygen demand 5 days (BOD_5) removals in treating pharmaceutical wastewater. The highest average COD and BOD_5 removals were achieved by the mesophilic HUASB

reactor treating high strength pharmaceutical wastewater at HRT of five days (average OLR 0.43 g COD/L-day); average COD removal was 90%, average effluent COD was 133 mg/L, average BOD₅ removal was 97% and average effluent BOD₅ was 51 mg/L. The COD and BOD₅ removals decreased when the HRT was decreased. The concentration of ammonia-nitrogen (NH₃-N) and total phosphorous (TP) increased during this study whereas the concentration of nitrate-nitrogen (NO₃-N) was constant and the concentration of total Kjeldahl nitrogen (TKN) slightly reduced.

Three kinetic models i.e. Monod, modified Stover-Kincannon and Grau second-order were applied in this study to determine the kinetics of pharmaceutical wastewater treatment using UASB and HUASB reactors. The results of kinetic model analysis indicated that Grau second-order fits well for estimates of kinetic coefficients in all reactors. High R^2 values ($R^2 > 0.9$) were obtained for a and b determinations for all reactors.

ABSTRAK

Kajian rawatan air buangan secara biologi telah diusahakan untuk merawat air buangan farmaseutikal selain daripada penisilin. Kajian telah dilakukan dalam dua fasa. Fasa pertama tertumpu pada kajian permulaan untuk menentukan kemungkinan rawatan biologi untuk merawat air buangan farmaseutikal. Rawatan secara biologi pada fasa pertama terdiri daripada dua tren rawatan; Tren 1 terdiri daripada satu "semi-anaerobic baffle reactor" (SABR) yang diikuti oleh sebuah "activated sludge process" (ASP) reaktor, sementara Tren 2 terdiri daripada satu ASP reaktor sahaja. Fasa kedua dijalankan pada proses-proses perawatan secara anaerob. Rawatan biologi anaerob air buangan farmaseutikal diusahakan menggunakan reaktor-reaktor "upflow anaerobic sludge blanket" (UASB) dan "hybrid upflow anaerobic sludge blanket" (HUASB). Reaktor UASB dan HUASB dioperasikan pada kondisi mesophilik ($35\pm 2^{\circ}\text{C}$) dan termophilik ($55\pm 2^{\circ}\text{C}$). Empat waktu tinggal hidrolis (HRT) diaplikasikan pada semua reaktor. Lumpur daripada satu loji rawatan air kumbahan domestik aerob digunakan sebagai benih biomasa pada semua reaktor.

Pada fasa pertama, reaktor-reaktor diisi dengan konsentrasi "chemical oxygen demand" (COD) ialah 607-1953 mg/L. Tren 1 (SABR-reaktor ASP) memperoleh penyisihan COD lebih tinggi pada rawatan air buangan konsentrasi tinggi (COD 1953 mg/L), tetapi Tren 2 memperoleh penyisihan COD lebih tinggi pada rawatan air buangan konsentrasi rendah (COD 635 mg/L). Biomasa aerob daripada satu loji rawatan air buangan domestik telah berjaya untuk digunakan sebagai benih biomasa pada reaktor-reaktor aerob dan semi-anaerob pada rawatan air buangan farmaseutikal selain daripada penisilin.

Pada fasa kedua, reaktor-reaktor diisi dengan influen konsentrasi rendah (COD 458-526 mg/L) dan influen konsentrasi tinggi (COD 1770-2217 mg/L). Reaktor-reaktor mendapatkan penyisihan COD yang lebih tinggi pada rawatan air kumbahan dengan influen konsentrasi tinggi. Hasil-hasil kajian menunjukkan bahawa performa reaktor dipengaruhi secara signifikan oleh jenis reaktor, HRT dan temperatur. Reaktor UASB dan HUASB mesophilik menunjukkan penyisihan COD

dan "biochemical oxygen demand 5 days" (BOD_5) yang lebih tinggi pada rawatan air buangan farmaseutikal. Purata penyisihan COD dan BOD_5 tertinggi diperoleh reaktor HUASB mesophilik pada penyisihan air buangan konsentrasi tinggi dengan HRT lima hari. Purata penyisihan COD ialah 90%, purata COD effluen ialah 133 mg/L, purata penyisihan BOD_5 ialah 97%, dan purata BOD_5 effluen ialah 51 mg/L. Penyisihan COD dan BOD_5 berkurang bilamana HRT dikurangkan. Konsentrasi ammonia-nitrogen (NH_3-N) dan total phosphorous (TP) meningkat pada kajian ini, sedangkan konsentrasi nitrate-nitrogen (NO_3-N) konstan dan konsentrasi total Kjeldahl nitrogen (TKN) menunjukkan sedikit penurunan.

Tiga model kinetik, yaitu Monod, modified Stover-Kincannon, dan Grau second-order diaplikasikan pada kajian ini untuk menentukan kinetik-kinetik rawatan air buangan farmaseutikal dengan menggunakan reaktor UASB dan HUASB. Hasil kajian model kinetik menunjukkan bahawa Grau second-order sesuai untuk pengiraan koefisien kinetik pada semua reaktor. Nilai R^2 yang tinggi ($R^2 > 0.9$) didapatkan untuk penentuan a dan b untuk semua reaktor.

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ABBREVIATIONS AND NOMENCLATURES

ADS	anaerobic digester sludge
ASP	activated sludge process
AF	anaerobic filter
AMBR	anaerobic migrating blanket reactor
BOD ₅	biochemical oxygen demand 5 days
COD	chemical oxygen demand
HRT	hydraulic retention time
HUASB	hybrid up flow anaerobic sludge blanket
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
NH ₃ -N	ammonia nitrogen
NO ₃ -N	nitrate nitrogen
OLR	organic loading rate
POME	palm oil mill effluent
TSS	total suspended solids
TVSS	total volatile suspended solids
TKN	total Kjeldahl nitrogen
TP	total phosphorus
RAS	return activated sludge
SABR	semi-anaerobic baffle reactor
SRT	sludge retention time
STP	sewage treatment plant
UAFB	upflow anaerobic fixed bed
UAFF	upflow anaerobic fixed film
UASB	upflow anaerobic sludge blanket
UASFF	upflow anaerobic sludge fixed film
WAS	waste activated sludge
a, b	kinetic constants (Grau kinetic model)
K_B	saturation value constant (modified Stover-Kincannon), in g/L·day
K_d	endogenous decay coefficient, in per day
K_s	half-velocity saturation constant (mg/L)
K_{s2}	Grau substrate removal rate constant, in per day
Q	flow rate of influent wastewater, in L/day
S_o	influent substrate concentration, in mg/L
S_e	effluent substrate concentration, in mg/L
U_{max}	maximum substrate removal rate (modified Stover-Kincannon), in g/L·day
V	volume of reactor, in L
V_b	volume of sludge bed, in L
X	biomass concentration in the reactor, in mg/L
X_e	biomass concentration of effluent wastewater, in mg/L
X_o	biomass concentration of influent wastewater, in mg/L
Y	cell yield coefficient, in mg VSS/mg COD

θ_c	solid retention time, in day
μ	specific growth rate, in per day
μ_m	maximum specific growth rate, in per day
θ_H	hydraulic retention time, in day

CHAPTER 1

INTRODUCTION

1.1 Background

The predominance of various diseases, the growth of population and the increase of healthcare product requirements were factors that ensured a steady growth of pharmaceutical industries. In Malaysia, the requirement of cosmetics and other pharmaceutical products, e.g. vitamins and food supplements also increased. Furthermore, the Malaysian consumers who were turning from conventional drugs to herbal products increased (NPCB, 2007). Therefore, not only the penicillin pharmaceutical products, but also the non-penicillin pharmaceutical products (both quantity and type) increased. The growth of non-penicillin pharmaceutical products influenced the manufacturing processes in the pharmaceutical industry.

Raw materials used by the pharmaceutical industry might be from medicinal plants, herbs, fruits, flowers, leaves, stems, roots, gums, etc. (Nandy and Kaul, 2001). The processes involved in pharmaceutical productions can be broken down into five categories which are (a) fermentation, (b) biological and natural extractions, (c) chemical synthesis, (d) mixing, compounding and formulating and (e) pharmaceutical research (US EPA, 2006). Therefore, the composition of pharmaceutical wastewater can vary widely from one effluent to another.

It is mandatory to treat wastewater to meet effluent discharge standards before its release into the environment. Physical, chemical and biological methods are widely used in wastewater treatment. Biological treatment methods can be divided into aerobic and anaerobic types. Aerobic processes, which are widely used for wastewater treatment, at least have two distinct disadvantages such as relatively high-energy requirement and high excess sludge production requires handling, treatment and disposal. Anaerobic processes, on the other hand, generate energy in the form of biogas and produce less sludge than aerobic processes. Therefore,

anaerobic treatment can be a lucrative alternative for treatment of pharmaceutical wastewater.

Anaerobic reactors can be influenced by environmental and/or operating conditions. Typical responses in anaerobic reactors include decrease in performance, accumulation of volatile fatty acids (VFA), drop in pH and alkalinity, change in biogas production and composition and sludge washout (Leitao et al., 2006). Methane-forming bacteria are strict anaerobes and are extremely sensitive to the presence of dissolved oxygen and changes in environmental and/or operating conditions such as alkalinity, pH and temperature. Therefore, the operation conditions must be periodically monitored and maintained within optimum ranges (Gerardi, 2003). However, there are certain unclear technical and design operation conditions which are necessary for the improvement of the stability and reliability of anaerobic treatment, especially treatment for specific wastewaters.

Several configurations of anaerobic treatment can be the alternatives for wastewater treatments system including an upflow anaerobic sludge blanket (UASB) reactor (Seghezzo, 2004). The UASB concept relies on the establishment of a dense sludge bed in the bottom of the reactor, in which all biological processes take place. The UASB reactor may replace the primary settler, the anaerobic sludge digester, the aerobic step (activated sludge, trickling filter, etc.) and the secondary settler of a conventional aerobic treatment plant. However, the effluent of UASB reactor usually needs further treatment, in order to remove remaining organic matter, nutrients and pathogens. The other configuration of anaerobic treatment is hybrid upflow anaerobic sludge blanket (HUASB) reactor. The HUASB combines the advantages of the UASB and anaerobic filter (AF) concepts. The HUASB consisting of UASB and AF has been applied to various industrial wastewater. The performance of UASB and HUASB reactors were influenced by many factors including organic loading rate (OLR), hydraulic load, sludge retention time (SRT), as well as operational temperature (Leitao, 2004). The OLR applied to the reactors depends on the influent concentration, flow rate and reactor volume; therefore also on the imposed hydraulic retention time (HRT).

Kinetic process has been used for the mathematical description of both anaerobic biological treatment processes (Seghezzo, 2004). Kinetic models of the anaerobic system can help to gain more insight into the process. The understanding of process kinetics is essential for the rational design and operation of biological wastewater treatment system and for predicting the system stability and treatment efficiency. Kinetic process plays an important role in the development and operation of anaerobic treatment systems.

1.2 Problem Statement

Pharmaceutical wastewater can affect the environment adversely, if discharged without proper treatment. Biological treatment is often carried out to reduce its organic content. In Malaysia, however, the use of anaerobic system for wastewater treatment is still not common. High rate anaerobic reactors such as UASB and HUASB can be attractive alternatives for pharmaceutical wastewater treatment.

1.3 Objectives of Study

- a. To observe the performance of semi-anaerobic and aerobic reactors in treating non-penicillin pharmaceutical wastewater
- b. To evaluate the performance of UASB and HUASB reactors in treating non-penicillin pharmaceutical wastewater
- c. To evaluate the effect of HRT and temperature on the performance of UASB and HUASB reactors
- d. To determine the kinetics of pharmaceutical wastewater treatment using UASB and HUASB reactors

1.4 Scope of Study

This study presents the performance of biological treatment, specifically anaerobic treatment for treating non-penicillin pharmaceutical wastewater. The study was divided into two phases. The first phase was conducted to observe the performance of semi-anaerobic and aerobic system. The second phase evaluated the anaerobic

treatment using UASB and HUASB reactors. Wastewater used in this study was taken from a non-penicillin based factory.

The study focused on the operating conditions of anaerobic treatment (i.e. HRT and temperature) and highlighted the use of different type of anaerobic reactors. The experimental investigation was performed using four bench-scale reactors. The two UASB reactors and two HUASB reactors were operated under mesophilic and thermophilic temperatures. The seed biomass for the reactors was taken from aerobic based sewage treatment plant.

1.5 Thesis Organisation

This thesis has been organized into the following five chapters:

Chapter 1 introduces the context of study about non-penicillin pharmaceutical wastewater biological treatment. Problem statement, objectives and scope of the study are presented in this chapter.

Chapter 2 presents a brief review of pharmaceutical wastewater and biological treatment to treat pharmaceutical wastewater. Factors that effect anaerobic treatment and reactor configurations are also reviewed in this chapter.

Chapter 3 presents the methodology of study that was applied to treat non-penicillin pharmaceutical wastewater.

Chapter 4 shows the results viz. Phase I used semi-anaerobic and aerobic treatment and Phase II was based on UASB and HUASB reactors. The experiment results are also discussed.

Chapter 5 summarizes the findings of the study on non-penicillin pharmaceutical wastewater biological treatment.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a brief review of pharmaceutical wastewater. Basic concepts and theories of biological treatment, especially anaerobic treatment are also introduced.

2.1 Pharmaceutical Wastewater

The prevalence of various diseases, the growth of population and the increase of healthcare needs were factors that ensured a steady growth of pharmaceutical industry. The key drivers that boosted the Malaysian pharmaceutical industries are medical tourism, specialist therapy, generic and over-the-counter drugs and food supplements. The current self-managing trend among Malaysian consumers is a major factor that has broadened the over-the-counter drug market, which is mainly driven by vitamin and dietary supplements. Malaysian consumers who are turning from synthetic allopathic drugs (conventional drugs) to herbal products to maintain health and prevent illnesses are on the increase (Kok, 2008).

In the year 2007, 27974 product registration applications were received by the National Pharmaceutical Control Bureau (NPCB) Malaysia that was established to implement quality control testing of pharmaceutical products. The numbers of prescription drugs, non-prescription drugs, traditional products and cosmetics registered by the Drug Control Authority (DCA) of NPCB were 449, 413, 1342 and 28403, respectively. Manufacturers layout plants which consist of 7 prescription manufacturers, 7 non prescription manufacturers, 13 traditional manufacturers, 10 cosmetic manufacturers and 2 veterinary manufacturers were evaluated by the Good Manufacturing Practices (GMP) of NPCB and a total of 301 manufacture licences were issued in the year 2007 (NPCB, 2007).

The composition of wastewater from industrial operations varies widely depending on the function and activity of the particular industry. Because of variation of flow rate

and water quality, it is often difficult to define the operation conditions for industrial activities (Metcalf & Eddy, 2003). Pharmaceutical industry includes manufacture, extraction, processing, purification and packaging chemical materials that are used as medications for humans or animals. Pharmaceutical manufacturing can be divided into two major stages: production of the active ingredient or drug and secondary processing or conversion of the active drugs into products suitable for administration (Cheremisinoff, 2001).

The major manufactured groups include:

- a. Antibiotics such as penicillin, streptomycin, tetracyclines, chloramphenicol and antifungal
- b. Other synthetic drugs, including sulfa drugs, anti-tuberculosis drugs, anti-leprotic drugs, analgesics, anesthetics and anti-malarials
- c. Vitamins
- d. Synthetic hormones
- e. Glandular products drugs of vegetable origin, such as quinine, strychnine and brucine, emetine and digitalis glycosides
- f. Vaccines and sera
- g. Other pharmaceutical chemicals

Their composition varies, depending on the product manufactured, the materials used in the process and other process details (Cheremisinoff, 2001).

Pharmaceutical wastewater, which include several organic solvents and other toxic chemicals, are generally treated aerobically. The alternative treatment is the anaerobic route that has lower cost of treatment and generates methane gas that can be used as energy. However, there are few reports on the anaerobic treatment of the pharmaceutical effluents. The most important merits of anaerobic treatment are the ability to treat high strength wastewater, low energy and space requirement, low sludge production, low operation cost and net benefit of energy generation. The production of biogas in the anaerobic organic degradation makes this process a feasible alternative to aerobic treatment methodology (Mohan et al., 2001).

The raw material used by the pharmaceutical factory might be from medicinal plants, herbs, fruits, flowers, leaves, stems, roots, seeds, gums, etc. In almost all pharmaceutical industries, the production processes are in batches. Therefore, the processes have a lack of homogeneity that leads to variation in wastewater quality and quantity. The wide fluctuations on the treatment units in terms of organic and hydraulic loadings might have a harmful effect on anaerobic processes and cause destabilization of the microbial populations leading to volatile fatty acids (VFA) accumulation that can acidify the reactor and inhibit methanogenic microorganisms (Nandy and Kaul, 2001).

2.2 Biological Wastewater Treatment

Biological methods of wastewater treatment can be either aerobic (in the presence of oxygen) or anaerobic (in the absence of oxygen). Aerobic processes, which are widely used for wastewater treatment, at least have two distinct disadvantages viz., relatively high-energy requirement and high excess sludge production. Excess sludge production requires handling, treatment and disposal. Anaerobic processes generate energy in the form of biogas (methane) and produce less sludge than aerobic processes. However, a certain prejudice against using anaerobic processes exists in tropical countries. Another reason is a serious lack of knowledge by the engineers on the design and operation of anaerobic systems (Seghezzo, 2004). The main advantages and drawbacks of anaerobic treatment are shown in Table 2.1 (Hall, 1992; Lettinga, 1996; Seghezzo, 2004; Seghezzo et al., 1998).

2.2.1 Anaerobic Process

Three different groups of bacteria are involved in the transformation of complex organics into simple molecules such as methane and carbon dioxide (Wiesmann et al., 2007). They are involved in three basic steps in the complete anaerobic oxidation process: hydrolysis, fermentation (also known as acidogenesis) and methanogenesis (Metcalf & Eddy, 2003; Vaccari et al., 2006). The three steps are illustrated schematically in Figure 2.1.

Table 2.1 Advantages and disadvantages of anaerobic treatment

Advantages
<ul style="list-style-type: none"> a. Low biological sludge production. The excess sludge is generally significantly lower than aerobic process, due to the slow growth rates of anaerobic bacteria. The excess sludge is generally well stabilized. b. High treatment efficiency. High removal efficiency can be achieved in anaerobic process, even at high organic loading rate (OLR). The anaerobic treatment is feasible for a wide range of waste and wastewater, i.e. complex in composition, a low and very high strength, low and high temperatures c. Low energy consumption, As long as no heating requirement is needed to reach the operational temperature and all reactor operations can be operated by gravity, the energy consumption for the reactor is almost negligible. d. Methane production. Instead of consuming energy, biogas is produced. e. Low nutrient and chemical requirements. An adequate and stable pH can be maintained without the addition of chemical. f. Valuable nutrients (nitrogen and phosphorus) are conserved which give high potential for irrigation. g. Low space requirement. When high OLR are applied, the area requirement for anaerobic reactor is small. h. Anaerobic biomass can be preserved without feeding for long period without any serious deterioration of their activity. i. Simple and flexible. The construction and operation of anaerobic reactor is relatively simple and can be applied on either a very large or a small scale.
Disadvantages
<ul style="list-style-type: none"> a. Low nutrient and pathogen removal. Nutrient removal is negligible and pathogens are only partially removed, especially when the anaerobic reactor is operated in low temperature. b. Require post treatment. Post treatment of the anaerobic effluent is generally required to achieve the discharge standard for organic matter, nutrients and pathogens. c. Long start-up. Due to the low growth rate of methanogenic organism, the start up takes longer as compared to aerobic processes, especially when no good inoculums is available. d. Possible bad odours. Hydrogen sulphide is produced during the anaerobic process, especially when there are high concentrations of sulphate in the wastewater. e. Require capable operators. The anaerobic reactor should be sufficiently understood by engineers and operators.

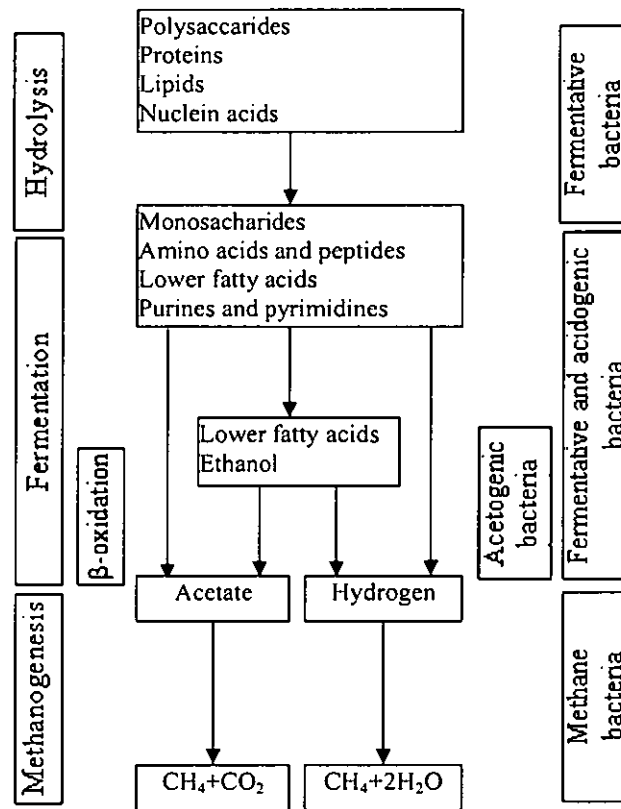


Figure 2.1 Anaerobic process schematic
(Metcalf & Eddy, 2003; Wiesmann et al., 2007)

The first step for most fermentation is hydrolysis in which particulate material is converted to soluble compounds that can then be hydrolyzed further to simple monomers. The monomers are used by bacteria that perform fermentation (Metcalf & Eddy, 2003). During hydrolysis step, macromolecular organic compounds entering the system are transformed hydrolytically from large and in many instances solid phase macromolecular materials (e.g., cellulose, grease, protein, microbial cells) into their smaller, soluble building blocks (e.g., amino acids released from protein, carbohydrates from polysaccharides, fatty acids from lipids and fats) (Vaccari et al., 2006). The monomers are directly available to the next group of bacteria (Bitton, 2005). During subsequent fermentation maintained by the anaerobic digestion process, one fraction of these hydrolyzed organics will eventually be oxidized to carbon dioxide, another fraction will be reductively converted to methane

and a third, comparatively smaller fraction will be assimilated anabolically into a new anaerobic cell mass (Vaccari et al., 2006).

The second step is fermentation where in amino acids, sugar and some fatty acids are degraded further (Metcalf & Eddy, 2003). Two different types of acidogenic reactions are involved: one and two-step conversions. The first mechanism produces acetate primarily (i.e., by means of an acetogenic conversion, encompassing reactions that produce organic acids directly). The second fermentative conversion involves intermediate production of volatile fatty acids (e.g., butyric and propionic acid) and alcohols, which are converted subsequently to acetate, hydrogen and carbon dioxide (Vaccari et al., 2006). Acidogenic bacteria produce extracellular enzymes (exoenzymes) for the hydrolysis of complex organic molecules. Carbohydrates are hydrolyzed down to monosaccharide and disaccharides, proteins into amino acids and lipids into fatty acids. These compounds are transformed to acetate and longer chain fatty acids as well as CO_2 and H_2 . The most important organics in wastewater are proteins, lipids and hydrocarbons. All can be utilized by acidogenic bacteria, which encompass a very large group of different, mostly facultative anaerobic bacteria (Wiesmann et al., 2007).

Proteins are hydrolyzed into amino acids by proteases, which function as exo-enzymes. A small amount of amino acids is used directly for growth (anabolism), while a large amount is converted to lower fatty acids, CO_2 , H_2 as well as NH_4^+ and is excreted (catabolism). Lipids are esters formed from glycerine, an alcohol with valence of three and fatty acids. These have been hydrolyzed previously by lipase enzymes. Glycerine can be partially used for anabolic reactions and is converted in part to lower alcohols (catabolism). Fatty acids cannot be used by acidogenic bacteria and are excreted. One part is totally used for protein synthesis and bacterial growth, while another part is converted into lower fatty acids (Wiesmann et al., 2007).

Acetogenic bacteria transform lower fatty acids such as butyrate and propionate into acetate, CO_2 and H_2 . It is of great importance that H_2 is oxidized by other anaerobic

bacteria. Otherwise, propionate concentrations would continually increase. Only a part of acetate is formed directly during fermentation (Wiesmann et al., 2007).

The third step, methanogenesis, is carried out by a group of methanogenic organisms (Metcalf & Eddy, 2003). Methanogenesis converts low molecular weight organic precursor species into gaseous end products at both ends of the carbon oxidation state range, including fully reduced methane and fully oxidized carbon dioxide. At this point, therefore, the overall process of anaerobic digestion will have biochemically converted a sizable fraction of an initial sludge residual into a far more kindly, possibly even energetically useful gaseous product (Vaccari et al., 2006).

Hydrogen and acetate must be utilized by methanogenic bacteria. They exhibit two main products of catabolic metabolism (Wiesmann et al., 2007). Two groups of methanogens are involved in methane production. One group, termed acetoclastic methanogens, split acetate into methane and carbon dioxide. The other group, termed hydrogen-utilizing methanogens, use hydrogen as the electron donor and CO_2 as the electron acceptor to produce methane. Anaerobic bacteria, termed acetogens, are also able to use CO_2 to oxidize hydrogen and form acetic acid. However, the acetic acid will be converted to methane, so the impact of this reaction is minor (Metcalf & Eddy, 2003).

Methane is not very soluble in water and carbon dioxide is in equilibrium with HCO_3^- and CO_3^{2-} as a function of pH. Most of the CO_2 and nearly all of the methane produced are desorbed, forming biogas bubbles, which can be recovered for utilization. Lower fatty acids such as butyrate and propionate can only be mineralized if the two catabolic products of acetogenic bacteria, i.e. hydrogen and acetate, are consumed by methanogenic bacteria. The methanogens are very old microorganisms, living on earth since before the oxygen-rich atmosphere was formed (Wiesmann et al., 2007).

The by-product from the anaerobic decomposition of organic matter in wastewater is methane gas. Normally, large quantities are not encountered in untreated wastewater

because even small amounts of oxygen tend to be toxic to the organisms responsible for the production of methane (Metcalf & Eddy, 2003).

2.3 Factors Affecting Anaerobic Treatment

Methane-forming bacteria are strict anaerobes and are extremely sensitive to changes in environmental and/or operation conditions such as alkalinity, pH and temperature. Therefore, the operation conditions must be periodically monitored and maintained within optimum ranges (Gerardi, 2003).

2.3.1 pH and Alkalinity

Most methanogens function well in a pH range of 6.7 to 7.4, but optimally at pH of 7.0 to 7.2 and the process may fail if the pH is close to 6.0. Acidogenic bacteria produce organic acids that decrease the pH of the bioreactor. Under normal operating conditions, this pH reduction is buffered by bicarbonate produced by methanogens. Under poor environmental conditions, the buffering capacity of the system can be upset, eventually stopping methane production. Acidity has more inhibitory effect to methanogens than to acidogenic bacteria. An increase in volatile acids level thus serves as an early indicator of system upset. The ratio of total volatile acids (as acetic acid) to total alkalinity (as calcium carbonate) has been suggested to be maintained below 0.1 (Bitton, 2005).

Alkalinity in wastewater results from the presence of the hydroxides (OH^-), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) of substances such as calcium, magnesium, sodium, potassium and ammonia. Borates, silicates, phosphates and similar compounds can also contribute to alkalinity (Metcalf & Eddy, 2003). One method for restoring the pH balance is to increase alkalinity by adding chemicals such as lime, anhydrous ammonia, sodium hydroxide, or sodium bicarbonate (Bitton, 2005). Alkalinity helps to resist changes in pH caused by the addition of acids. It is determined by titrating against a standard acid. In practice, alkalinity is expressed in terms of calcium carbonate (CaCO_3) (Metcalf & Eddy, 2003).

The most significant negative factor that can affect the economics of anaerobic versus aerobic treatment is the possible need to add alkalinity. Alkalinity concentrations of 2000 to 3000 mg/L as CaCO_3 may be added in anaerobic processes to maintain an acceptable pH with the high gas phase CO_2 concentration. If the amount of alkalinity is not available in the influent wastewater or can not be produced by the degradation of protein and amino acid, a significant cost may be incurred to purchase alkalinity, which can affect the overall economic of the process (Metcalf & Eddy, 2003).

With the high CO_2 content (typically in the range from 30 to 50 percent) in the gas produced in anaerobic treatment, alkalinity concentration in the range from 2000 to 4000 mg/L as CaCO_3 is typically required to maintain the pH at or near neutral (Metcalf & Eddy, 2003).

2.3.2 Temperature

Temperature is very important in assessing the overall efficiency of a biological treatment process. Temperature not only influences the metabolic activities in the microbial population but also has a strong effect on gas-transfer rates (Seghezzo, 2004). There are two optimal ranges for process operation to produce methane: from 30 to 40°C (the mesophilic range is from 15 to 40°C) and 50 to 60°C (the thermophilic range is for temperatures above 40°C). The psychrophilic range is temperatures below 15 to 20°C (Droste, 1997). Methane production has been documented under a wide range of temperatures ranging between 0°C and 97°C (Bitton, 2005). Methane has been produced at temperatures down to 10°C or lower, but for reasonable rates of methane production, temperatures should be maintained above 20°C. Rates of methane production approximately double for each 10°C temperature rise (Droste, 1997). Reactor temperatures of 25 to 35°C are generally preferred to support optimal biological reaction rate and to provide stable treatment (Metcalf & Eddy, 2003). Methanogens are very sensitive to even small changes in temperature. Thus, mesophilic digesters must be designed to operate at a temperature of 30 to 35°C for their optimal functioning. As regards the utilization of volatile acids by methanogens, a decrease in temperature leads to a decrease of the maximum

specific growth rate (μ_{\max}), while the half-saturation constant K_s increases (Bitton, 2005).

Loading rates must decrease as temperature decreases to maintain the same extent of treatment (Droste, 1997). Thermophilic treatment allows higher loading rates and is also beneficial to greater destruction of pathogens (Bitton, 2005). However, operation in the thermophilic range is not generally practical because of the high heating energy requirement (Droste, 1997).

2.3.3 Hydraulic Retention Time (HRT)

The operating hydraulic retention time (HRT), which depends on wastewater characteristics and environmental conditions, must be sufficient to allow metabolism by anaerobic microorganisms in digesters (Bitton, 2005).

2.3.4 Chemical Composition of Wastewater

There are significant differences in nutrient requirements between aerobic and anaerobic biological treatment processes. These differences are due to the unique needs of methane-forming bacteria and the lower cell (sludge) yield of fermentative bacteria as compared to aerobic bacteria. These two treatment requirements may be grouped as macronutrients and micronutrients. Macronutrient requirement for anaerobic biological treatment processes are much lower than the requirement for aerobic biological treatment (Gerardi, 2003).

Phosphorus is important in cellular energy transfer mechanisms via adenosine triphosphate (ATP) and polyphosphates. Biological phosphorus removal is realized by creating conditions favorable for the growth of phosphate-accumulating organisms (PAOs). The PAOs assimilate acetate and produce intracellular polyhydroxybutyrate (PHB) storage product using energy available from stored polyphosphate. An initial anaerobic zone allows the PAOs to take up VFAs into their cells and store them as PHB. The polyphosphate stored just prior to this is oxidized and used as an energy source, producing ATP; and it is thereby released into the liquid phase (Figure 2.2).

The anaerobic uptake of organic matter is inherently related to the accumulated polyphosphate. Some glycogen that contained in the cell is also used. Concurrent with the acetate uptake is the release of orthophosphate (O-PO_4), as well as magnesium, potassium and calcium cations. The PHB content in the PAOs increases while the polyphosphate decreases (Metcalf & Eddy, 2003; Wiesmann et al., 2007).

In anaerobic zone, concentrations of orthophosphate as high as 40 mg/L can be measured in the liquid as compared to wastewater influent concentration of 5 to 8 mg/L. The high concentration of O-PO_4 can be taken as indication that phosphorus release by the bacteria has occurred in this zone. Significant amounts of poly- β -hydroxybutyrate (PHB) are found stored in bacteria cells (Metcalf & Eddy, 2003).

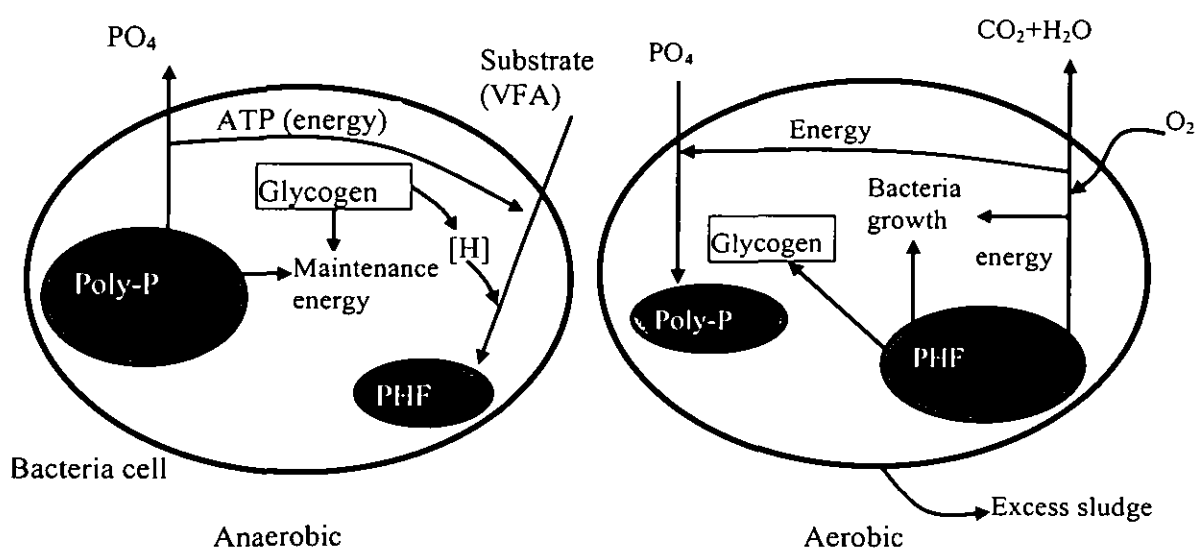


Figure 2.2 Mechanism of biological phosphorus removal
(Wiesmann et al., 2007)

2.4 Upflow Anaerobic Sludge Blanket (UASB) Reactor

The UASB process uses suspended biomass, but the gas-liquid-solids separation system is integral with the bioreactor. More importantly, the environmental conditions created in the bioreactor can result in the development of large, dense, readily settleable particles called granules, which allow very high concentrations of

suspended solids to be accumulated. These high suspended solids concentrations allow significant separation between the sludge retention time (SRT) and HRT and operation at relatively short HRT, often on the order of two days or less (Grady et al., 1999).

Influent wastewater enters the bottom of the bioreactor through a distribution system that is designed to provide relatively uniform flow across its cross section. A dense slurry of granules forms in the lower portion of the bioreactor and the combined effects of the influent wastewater distribution and gas production result in mixing of the influent wastewater with the granules. Treatment occurs within the dense blanket of granules (Grady et al., 1999). Inside these porous particles, fatty acids and biogas are formed. The reaction rate of the process is controlled by diffusion, convection and reaction inside the pores. Ascending biogas bubbles keep the particles partially fluidized (Wiesmann et al., 2007). For some wastewaters, a much less dense flocculent sludge also develops and this accumulates on top of the blanket of granules. Other wastewaters contain suspended solids that are not trapped in the granular sludge and these solids also accumulate as a flocculent sludge blanket overlying the granules (Grady et al., 1999).

The treated effluent exits the granular and flocculent sludge zones and flows upward into the gas-liquid-solids separator. A variety of configurations can be used for this device. The device often consists of a gas collection hood with a settler section above it (Grady et al., 1999). At the top of the UASB, the gas bubbles are separated from the water in hoods and the rising flocs, which show a lower settling rate, are carried up by the gas/liquid flow. Gas is collected in the hoods and removed (Wiesmann et al., 2007). Gas bubbles cause some granular and flocculent solids (particularly small granules) to rise through the bioreactor and enter the gas-liquid-solids separator. Gas separation occurs in the hood area, thereby allowing some of this suspended material to return directly to the solids blanket. Gas collects in the upper inverted V section of the hood and is removed from the bioreactor. Liquid with some entrained solids flows out of the hood into the settler section where liquid-solids separation occurs. Clarified effluent overflows to the weirs and effluent is discharged

while separated solids settle back into the reaction zone. Design of the gas-liquid-solids separation device requires insight into the physical processes occurring there and experience with specific devices in a variety of applications (Grady et al., 1999). The example of UASB schematic diagram is shown in Figure 2.3.

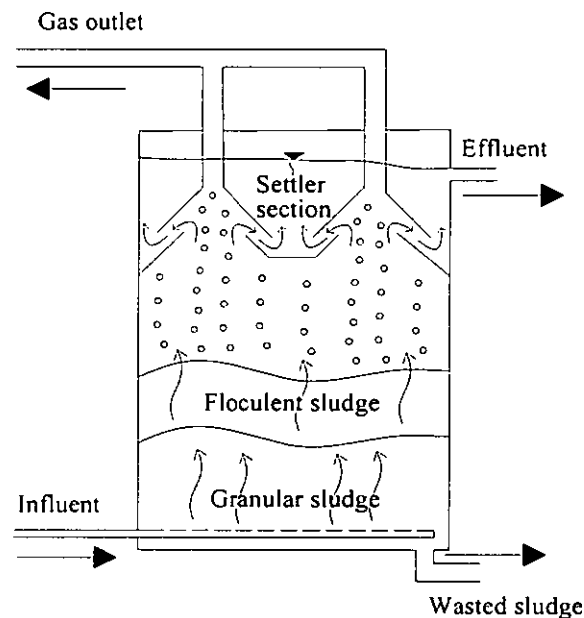


Figure 2.3 UASB Reactor
(Grady et al., 1999; Wiesmann et al., 2007)

2.5 Hybrid Upflow Anaerobic Sludge Blanket (HUASB) Reactor

Biofilm reactors utilize a fixed film approach for efficient anaerobic treatment of wastewater. Support media (rock, gravel, plastics, etc.) or biomass carrier is added to favour the microorganisms growth on the surface of media (Bitton, 2005; Wiesmann et al., 2007). The bulk of anaerobic microorganisms grow attached to the filter media; however, some form flocs that become trapped inside the filter media. The upflow system in the reactor helps to retain suspended solids in the column. The physical attachment prevents biomass washout, hence it leads to high values of sludge concentration and SRT. The example of anaerobic fixed film and HUASB reactors schematic diagram is shown in Figure 2.4.

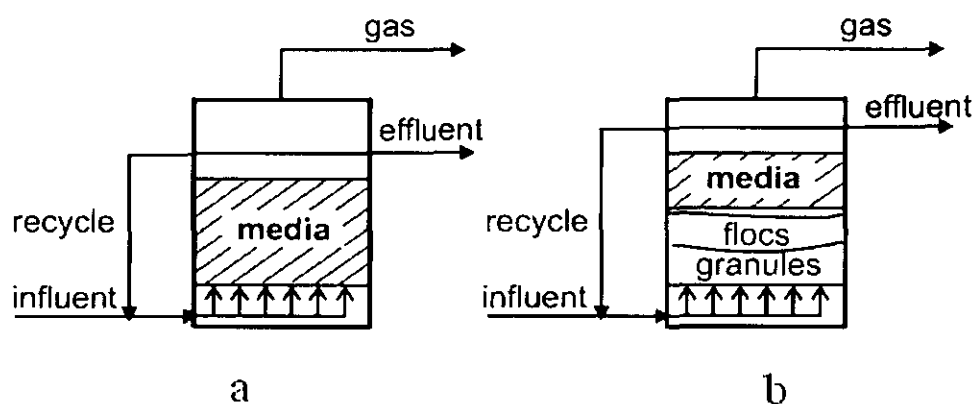


Figure 2.4 (a) Anaerobic fixed film reactor and (b) HUASB reactor
(Wiesmann et al., 2007)

The HUASB combines the advantages of the UASB and anaerobic filter concepts. The HUASB consisting of UASB and AF has been applied to various industrial wastewater such as palm oil mill effluent (POME) (Najafpour et al., 2006), chemical synthesis pharmaceutical (Oktem et al., 2007), complex phenolic mixture simulated coal (Ramakrishnan and Gupta, 2008), bulk drug pharmaceutical (Sreekanth et al., 2009), etc. On the top of an UASB reactor, a fixed bed reactor with a relatively short bed of synthetic media is installed and it was operated as HUASB reactor (Wiesmann et al., 2007). The HUASB reactors could also become a preferred option for pharmaceutical wastewater due to its operation, advantages over other reactor configurations (Oktem et al., 2007).

2.6 Pharmaceutical Wastewater Anaerobic Treatment

Table 2.2 shows the previous studies on anaerobic treatment of pharmaceutical wastewater. Oktem et al. (2007) studied the performance of a lab-scale HUASB reactor treating pharmaceutical wastewater. The pharmaceutical wastewater was collected from a chemical synthesis based pharmaceutical factory, whose main products were bacampicilline and sultampicilline tosylate. The HUASB consisted of a UASB portion and an anaerobic filter portion and was operated under different operating conditions. Polypropylene pall rings were used as filter media. The reactor was seeded by a granular sludge taken from a full-scale UASB reactor treating an alcohol distilling industry wastewater.

Table 2.2 Pharmaceutical wastewater treatment studies

Type of treatment	Temp (°C)	Wastewater	HRT	Initial COD (mg/L)	Removal COD (%)	Reference
UASB and activated sludge (semi-pilot plant)	30	Biosynthetic pharmaceutical	2.3 d	7140-10410	92.2% (UASB)	(Jenicek et al., 1996)
UAFF (bench scale)	35	Herbal based pharmaceutical	6, 5, 1.5, 1.25 d and 20 h	5000-80000	76-98	(Nandy and Kaul, 2001)
HUASB (UASB-AF) (bench scale)	N/S	Chemical synthesis based pharmaceutical	1-3 d	6000-27000	65-83	(Oktem et al., 2007)
HUASB (UASB-AF) (bench scale)	55±3	Bulk drug pharmaceutical	N/S	13000-15000 (OLR 1-12 g COD/L)	65-75	(Sreekanth et al., 2009)
Anaerobic batch reactor	37	Pharmaceutical, brewery, paper and amino acid producing industries (diluted)		1950-9230		(Martinez et al., 2005)
Anaerobic suspended film contact (bench scale)	35±2	Bulk drug manufacturing	8 d	23700-24500	30-82	(Mohan et al., 2001)
Expanded granular sludge bed anaerobic reactor	15	Pharmaceutical containing solvent	48, 24, 12 and 6 h.	5-20 kg COD/m ³ day (OLR)	60-80	(Enright et al., 2005)

Table 2.2 (Continued)

Type of treatment	Temp (°C)	Wastewater	HRT	Initial COD (mg/L)	Removal COD (%)	Reference
Packed bed anaerobic (bench scale)	35±2	Organic synthesis pharmaceutical	N/S	23000-31000 mg/L	80-98	(Nacheva et al., 2006)
Aerobic biological treatment (batch reactor)	30- 70 C	Pharmaceutical (untreated)	96 h	7320±160	38-62% (30 C-60 C)	(Lapara et al., 2001)
Anaerobic baffled reactor ^a and biofilm airlift suspension reactor ^b (pilot scale)	35 C	Antibiotic pharmaceutical	1.25 d and 2.5 d ^a ; 5.0- 12.5 h ^b	9736-19862	87%	(Zhou et al., 2006)

The OLR was gradually increased from 3 to 9 kg COD/m³·day to determine the relationship between COD removal and OLR in HUASB reactor. The COD removal efficiency was found to decrease gradually with increase in OLR. The COD removal efficiencies of 83% and 79% were achieved at OLR of 4 kg COD/m³·day and 5 kg COD/m³·day, respectively. Moreover, at the OLR of 6 kg COD/m³·day and HRT of two days, the COD removal efficiency was 75%. When the OLR increased from 6 to 7 kg COD/m³·day, the HUASB reactor performance did not decline significantly. On the other hand, when the OLR increased from 8 to 9 kg COD/m³·day, the COD removal efficiency showed a drastic decrease from 65 to 28% (Oktem et al., 2007).

Sreekanth et al. (2009) investigated the performance of a thermophilic HUASB reactor at different OLRs. The HUASB reactor was used to treat wastewater from a bulk drug pharmaceutical industry whose main product was terbinafine hydrochloride. A 17 L lab scale HUASB reactor with PVC rings at the middle of the reactor was used. The seed sludge was taken from a full-scale UASB reactor that treated a slaughterhouse wastewater. The COD concentration varied from 13000 to 15000 mg/L and BOD₅ concentration varied from 7000 to 7500 mg/L. The BOD: COD ratio ranged from 0.45 to 0.6, which was pleasant to biological treatment.

The HUASB reactor was studied at different OLRs. The COD and BOD₅ removals ranged from 65 to 75% and 80 to 94%, respectively, were obtained at the optimum OLR of 9 kg COD/m³·d. The methane content ranged from 60 to 70% and specific methanogenic activity (SMA) was 320 mL CH₄/g VSS·d. The biogas production ranged from 300 to 500 mL/g COD. Sreekanth et al. reported that the VFA concentrations varied from 100 to 400 mg/L as acetic acid at the OLR of 1 to 11 g COD/L·day, respectively. It indicated no loss of methanogenic potential in the mixed biomass. However, when the OLR increased suddenly from 2 to 5 g COD/L·day, the VFA concentration also increased from 400 to 2500 mg/L as acetic acid. It indicated methanogenic inhibition due to toxicity of bulk drug industrial effluent.

The application of hybrid reactors to the treatment of pharmaceutical wastewater is limited. No study was carried out on the thermophilic treatment of bulk drug pharmaceutical wastewater, although thermophilic process offers several benefits such as an increased degradation rate for organic solids, a high gas production rate, improved solid liquid separation, increased disinfection of pathogenic organisms and eliminating the cooling process for effluent of high temperature wastewater.

Jenicek et al. (1996) reported the anaerobic treatment of biosynthetic pharmaceutical wastewater using a semi pilot scale UASB reactor and an activated sludge system. The UASB reactor was operated at 30°C and obtained a COD removal of 92.2%. The residual COD in the anaerobic effluent was about 800 mg/L. Moreover, the UASB and activated sludge process obtained the COD removal of 97.5% at HRT of 2.3 days. The average COD and BOD₅ concentrations were 7140 and 4500 mg/L, respectively. The BOD₅/COD ratio was 0.63, which was relatively high and indicated good biodegradability. Jenicek et al. (2001) also reported that in the pharmaceutical factory, the fluctuation of the wastewater characteristics was very high (COD 2500-31500 mg/L).

Biotreatability of pharmaceutical wastewater using an anaerobic suspended film contact reactor was studied by Mohan et al. (2001). The reactor was designed to achieve effective contact with the anaerobic biomass in suspended form with the organic load. The BOD₅/COD ratio of the pharmaceutical wastewater from a large bulk drug-manufacturing unit was in the range of 0.4 to 0.6, which is amenable to anaerobic treatment. The reactor was operated at HRT of eight days with a working volume of 8 L. Mohan et al. (2001) confirmed that the increase in OLR from 2 to 10 g COD/day increased the COD removal rate. The COD removal ranged from 30 to 82%. However, at OLR of 20 g COD/day, the COD removal decreased. This was attributed to the micro toxic effect of high organic load on the microorganisms. The pH value of the effluent ranged from 6.8 to 8.2, which were well within the optimum pH range for methanogenesis. The methane content in the reactor was

found to be 60 to 70%. The gas analysis showed it was composed of 70% methane, 26% CO₂ and 4% N₂ (Mohan et al., 2001).

Applicability of anaerobic treatment of herbal-based pharmaceutical wastewater was studied at laboratory-scale by Nandy and Kaul (2001). An upflow anaerobic fixed film (UAFF) reactor was used to treat influent COD concentration of 5000-80000 mg/L. The COD removals ranged from 70 to 97% and 58 to 94% at HRTs of 5 and 2.5 days, respectively. The UAFF reactor was operated at 35°C. Herbal pharmaceutical wastewater distinguishes itself due to its high content of organic pollutant and its high acidic nature. Among the wide range of anaerobic reactor systems developed for the treatment of high strength wastewaters, UAFF reactor system has emerged with more successful operation (Nandy and Kaul, 2001).

Biological degradation of organic synthesis pharmaceutical wastewater was studied by Nacheva et al. (2006) using packed bed anaerobic mesophilic reactors. The pharmaceutical wastewater contained high organic matter and very low TSS. Five different support materials were used in the anaerobic reactor to treat pharmaceutical wastewater with influent COD concentration of 23000 to 31000 mg/L at temperature of 35±2°C. The reactors were fed with wastewater from organic synthesis processes that were performed in a chemical pharmaceutical plant. COD removal of 80 to 90% was obtained in the reactors with sand, anthracite and black tezontle at OLR of 3.6 kg/m³·day. Whereas, the reactor with granular activated carbon (GAC) had a better performance, which had COD removal higher than 95% and 80% at OLR of 17 and 26 kg/m³·day, respectively. The reactor that used GAC as support material, obtained greater biodegradation rates than the rest of the materials and process was more resistant to organic load increases, inhibition effects and toxicity (Nacheva et al., 2006).

Enright et al. (2005) studied low temperature anaerobic biological treatment of solvent containing pharmaceutical wastewater. Two identical expanded granular sludge bed (ESGB) anaerobic reactors were operated at 15°C and OLR of 5 to 20 kg COD/m³·day. COD removal efficiencies of 60-70% were achieved in these

studies. The reactors were operated at HRTs of 48, 24, 12 and 6 hours and the COD removal increased from 78 to 85% at a decreasing HRT of 48-24 hours. However, the COD removal decreased while the HRTs were decreased from 24 to 12 hours and 12 to 6 hours. The methane content decreased with decreasing HRT (Enright et al., 2005).

An active methanogenic biomass developed with a rapid start up with seeded sludge from an anaerobic reactor treating citric acid production wastewater and from an anaerobic reactor treating industrial alcohol production wastewater, even though the seed sludge was taken from different operation temperatures. Overall, the results of the study indicated the feasibility of psychrophilic (<20°C) treatment of pharmaceutical solvent containing.

Anaerobic and aerobic treatment of high strength pharmaceutical wastewater was evaluated by Zhou et al (2006). A batch test was performed to study the biodegradability of wastewater and based on the batch test, a pilot scale system composed of anaerobic baffled reactor followed by a biofilm airlift suspension reactor was conducted. The anaerobic bioreactor was operated at the temperature of 35°C and the influent COD ranged from 9736 to 19862 mg/L. The anaerobic baffled reactor results showed the effluent COD ranged from 1432 to 2397 mg/L at HRT of 1.25 day and 979 to 1749 mg/L at HRT of 2.5 day, respectively. On the other hand, the effluent from the aerobic reactor varied between 256 and 355 mg/L at HRTs of 5 to 12.5 hours. The wastewater also contained antibiotic substances with ampicillin and aureomycin concentrations of 3.2 and 1.0 mg/L, respectively. The anaerobic bioreactor could partially degrade the antibiotics while the aerobic reactors showed insignificant antibiotics removal. The ampicillin and aureomycin removal efficiencies in the anaerobic reactor were 16.4% and 25.9% at HRT of 1.25 days and 42.1% and 31.3% at HRT of 2.5 days, respectively, while in the aerobic reactor, the removal efficiencies of the antibiotics were less than 10% (Zhou et al., 2006).

The effect of temperature in aerobic biological pharmaceutical wastewater treatment was studied by Lapara et al. (2001) using batch reactors. The reactors were operated

at 5°C intervals from 30 to 70°C. Soluble COD removal efficiency declined as temperature increased from 30 (62%) to 60°C (38%). Aerobic biological treatment failed to occur at temperature higher than 60°C (Lapara et al., 2001).

2.7 Anaerobic Reactor Seeded with Aerobic Sludge

Due to limited number of thermophilic anaerobic digesters in operation, it was often difficult to start up a new one using sludge from an existing reactor as seed. However, most researchers consider mesophilic anaerobic sludge to be a satisfactory inoculum for the thermophilic anaerobic reactor, because it is grown in a similar anaerobic environment (Kim and Speece, 2002).

Kim and Speece (2002) evaluated the start up performance of anaerobic digestion using two different sources of seed sludge. Anaerobic digester sludge (ADS) and aerobic waste activated sludge (WAS) were used as seed sludge for anaerobic digesters at mesophilic (35°C) and thermophilic (55°C) conditions. The study was conducted in two experiments. First, thermophilic anaerobic reactors were used to investigate start-up performance with a feed of calcium acetate and calcium propionate. The WAS seeded reactor started to produce CH₄ soon after acetate feeding without a lag time, while the ADS seeded reactor had a lag time of 10 days. The experiment was conducted without temperature acclimation for the thermophilic sludge. The results indicated that the WAS reactor had a significant capacity to biodegrade acetate anaerobically (Kim and Speece, 2002).

Kim and Speece (2002) also compared the methanogenic activity of anaerobic digestion seeded by the WAS and ADS. Both reactors were operated under mesophilic and thermophilic temperatures. The WAS seeded reactor produced more CH₄ per unit amount of seeded VSS than the ADS reactor. The WAS reactor performance was better than the ADS reactor at both mesophilic and thermophilic conditions. The WAS reactor at mesophilic temperature biodegraded propionate much faster than at thermophilic temperature. When acetate was used as the feed, the WAS reactor started producing CH₄ within five days at both mesophilic and thermophilic reactors. On the other hand, the mesophilic ADS reactor started

producing CH₄ very soon, i.e. within one day while the thermophilic ADS reactor started producing CH₄ very late, i.e. within 30 days (Kim and Speece, 2002).

The results showed the validity of WAS as a seed source for anaerobic digestion. The WAS reactor obtained much better performance than the ADS reactor at both mesophilic and thermophilic temperatures for both acetate and propionate degradations. Kim and Speece (2002) hypothesized that there might be anaerobic bacteria with high activity in the WAS. The other was that dominant bacteria in WAS might function in micro zones with anaerobic conditions and that methanogens and propionate degrading organism might be much more tolerant of aerobic conditions than previously thought.

CHAPTER 3

METHODOLOGY

This study was conducted to evaluate the performance of biological treatment for treating non-penicillin based pharmaceutical wastewater. The study was conducted in two phases; Phase I used two trains of reactors (semi-anaerobic-aerobic and aerobic), meanwhile Phase II used four anaerobic reactors. Phase I was performed as a preliminary study of pharmaceutical wastewater treatment. In this phase, an aerobic biomass from a sewage treatment plant was evaluated as seed biomass in biological process reactor. In Phase II, only anaerobic reactors seeded by using the same source of biomass as in Phase I were investigated. Figure 3.1 shows the schematic diagram of this study.

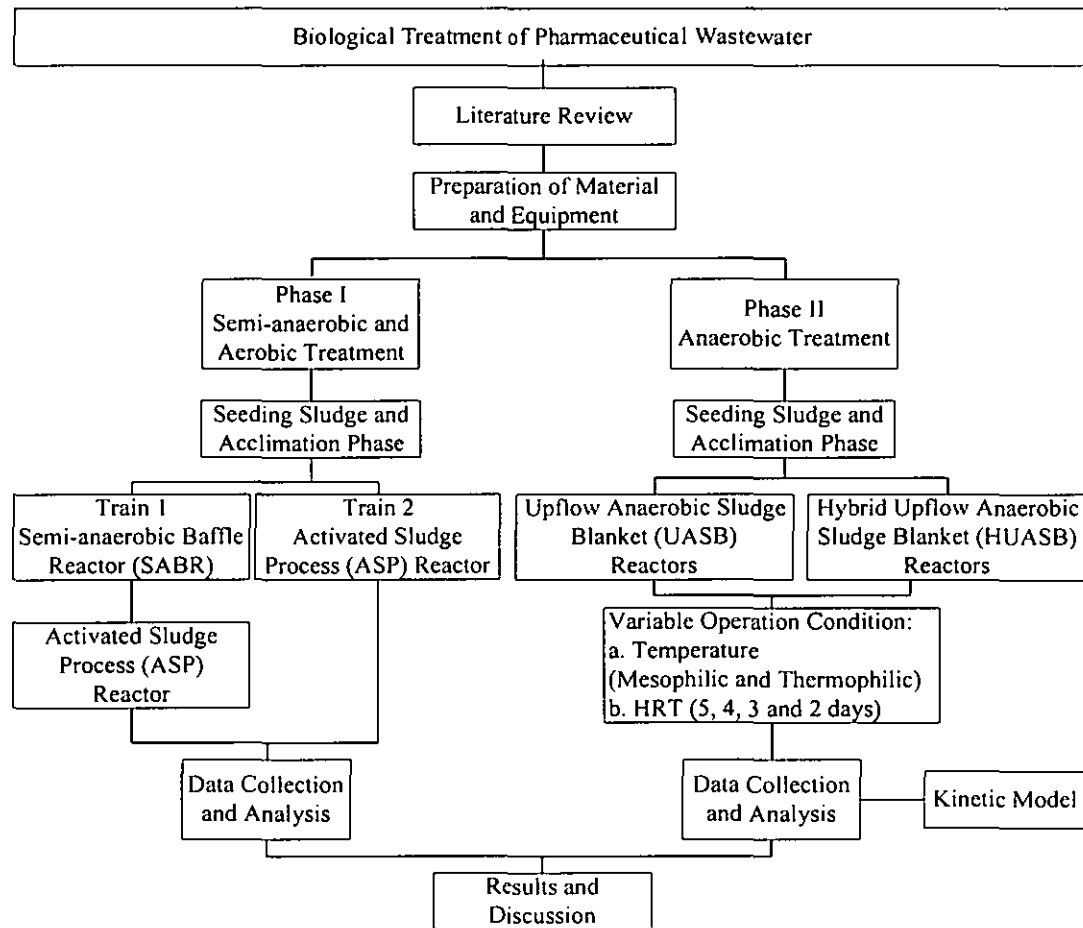


Figure 3.1 Schematic diagram of study

3.1 Phase I: Treatment of Pharmaceutical Wastewater Using Semi-anaerobic and Aerobic Reactors

3.1.1 Phase I Experimental Procedure

The biological treatment in this study consisted of two treatment trains; Train 1 which consisted of a semi-anaerobic reactor followed by an aerobic reactor while Train 2 consisted of only an aerobic reactor. A schematic diagram of the treatment trains used in this study is shown in Figure 3.2.

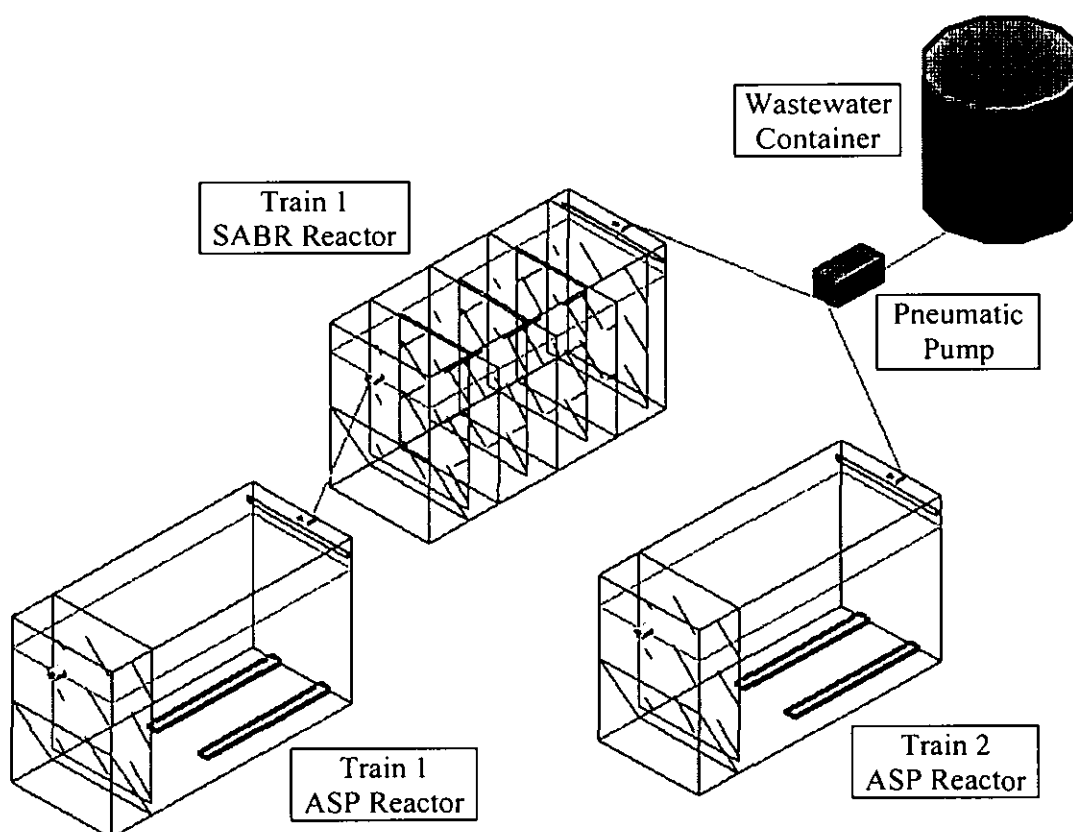


Figure 3.2 Phase I experimental diagram

3.1.2 Semi-anaerobic Baffle Reactor (SABR)

A laboratory-scale semi-anaerobic baffle reactor was used in Train 1. The acrylic reactor was fabricated with internal dimensions of 48 cm x 20 cm x 29 cm (L x B x H). The total volume was 27.8 L and the working volume was 23 L (liquid height of 24 cm). The reactor was operated as vertical flow and under ambient

temperature ($27 \pm 3^\circ\text{C}$). The reactor consisted of seven baffle walls and without cover at the top. The Train 1 SABR used in this study is shown in Figure 3.3a.

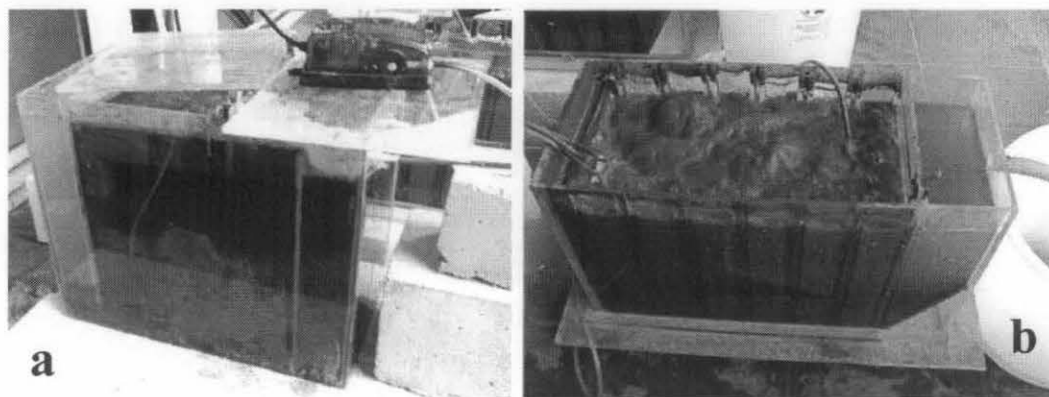


Figure 3.3 (a) Train 1 SABR and (b) Train 1 ASP reactor

3.1.3 Activated Sludge Process (ASP) Reactor

Laboratory-scale activated sludge process (ASP) reactors were used in Train 1 and Train 2. The acrylic ASP reactors consisted of two sections: aeration and settling sections. The aeration section had internal dimensions of 40 cm x 20 cm x 29 cm (L x B x H). The total volume was 23.2 L and the working volume was 19.2 L (liquid height of 24 cm). The settling section had internal dimensions of 8 cm x 20 cm x 24 cm (L x B x H). The slope of settling section was 45° . The flow was introduced in the settling section at the bottom. Samples of the effluent were taken from the settling section. Diffuse aerators were used in the activated sludge reactors. The Train 1 ASP reactor and Train 2 ASP reactor used in this study are shown in Figure 3.3b and Figure 3.4, respectively.

3.1.4 Source of Wastewater

Pharmaceutical wastewater was collected from a non-penicillin based pharmaceutical factory in Seri Iskandar, Perak, Malaysia. Wastewater samples were collected every two or three weeks. The biological reactors were fed with the pharmaceutical wastewater without pre-treatment. The wastewater was stored in a cold room at 4°C before use. The characteristics of pharmaceutical wastewater during Phase I are shown in Table 3.1.

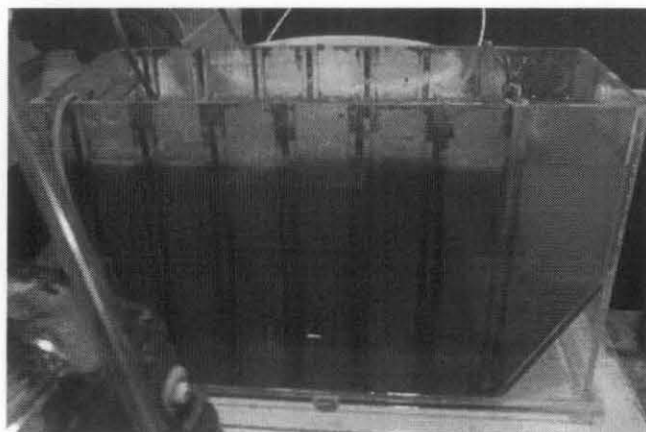


Figure 3.4 Train 2 ASP reactor

Table 3.1 Characteristic of pharmaceutical wastewater (Phase I)

Parameter	Concentration (mg/L)
BOD ₅	462-1299
COD	607-1953
TSS	7-38
NH ₃ -N	7.4-24.8
NO ₃ -N	0.3-0.8
Total Phosphorus	2.54-6.57
pH	5.17-6.65

3.1.5 Seed Biomass and Acclimatization Phase

The seed biomass for ASP reactors was taken from return activated sludge (RAS) of Universiti Teknologi PETRONAS's (UTP) Sewage Treatment Plant (STP), while the seed biomass for semi-anaerobic reactor was taken from sludge thickener. The semi-anaerobic reactor was inoculated with 8.5 L sludge and ASP reactors were inoculated with 10 L sludge. The seed biomass for semi-anaerobic reactor was taken from sludge thickener in order to obtain high sludge concentration. For initial acclimatization, all reactors were batch-fed daily with pharmaceutical wastewater for 7 days. After 7 days, both trains were continuously fed with pharmaceutical wastewater at a flow rate of 7.7 L/day.

3.2 Phase II: Treatment of Pharmaceutical Wastewater Using UASB and HUASB Reactors

3.2.1 Phase II Experimental Procedure

The experimental investigation was carried out utilising four reactors. Two reactors were UASB and two reactors were HUASB. The schematic diagrams of the four 5 L UASB and HUASB laboratory-scale reactors used in this study are shown in Figure 3.5 and Figure 3.6, respectively. One UASB and one HUASB were operated under mesophilic conditions ($35\pm 2^\circ\text{C}$) and the others were under thermophilic conditions ($55\pm 2^\circ\text{C}$). Temperatures were maintained by heating jackets that were connected to temperature control devices. Each temperature control device worked based on temperature inside the reactor, which was measured by a thermometer. Pharmaceutical wastewater was continuously fed to the reactors using a peristaltic pump (Master Flex, Cole Palmer). Four HRTs i.e. five, four, three and two days were used for all reactors during this study. A stirrer was used in feed tank to ensure a homogeneous wastewater influent.

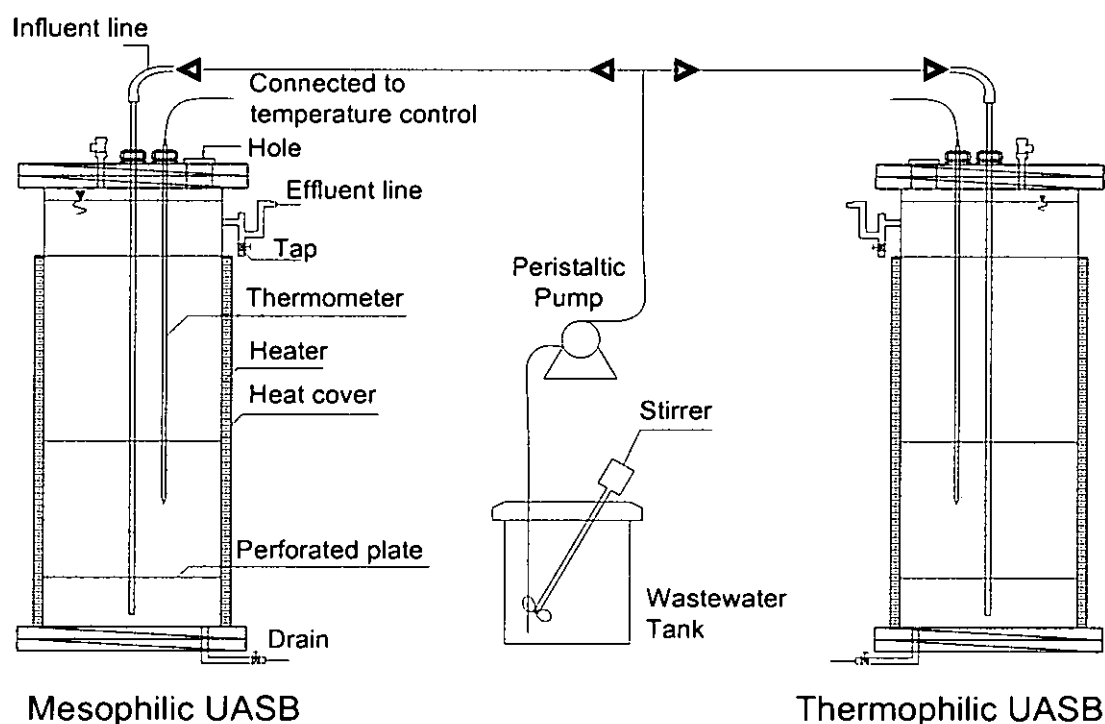


Figure 3.5 Phase II schematic diagram of UASB reactors

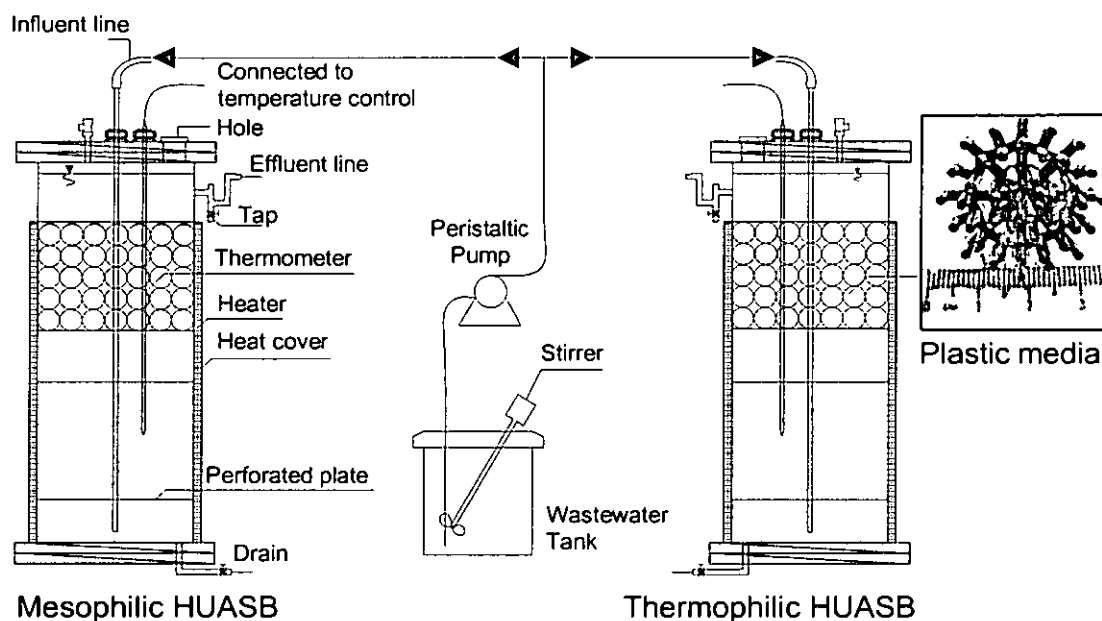


Figure 3.6 Phase II schematic diagram of HUASB reactors

3.2.2 UASB Reactors

The UASB reactors (Armfield Anaerobic Digester W8) with total liquid volume of 5 L (empty volume 5.5 L) were used throughout the study (Figure 3.7a). The UASB reactors were made from an acrylic column with 140 mm of diameter (internal) and 355 mm of height (330 mm water depth). A perforated plate of 3 mm thickness with perforations of 8 mm diameter was placed at the bottom of the column in order to ensure proper distribution of flow through the reactor. The wastewater entered at the centre of the UASB reactors and flowed upward through the perforated plate. Sludge sampling ports were provided at the bottom of each reactor. The UASB reactors had 2 cm clear gap above the outlet to separate the gas from the wastewater, so the empty volume of reactors was 5.5 L.

3.2.3 HUASB Reactors

The HUASB reactors had a UASB portion (3.75 L) under a fixed film portion (1.25 L) (Figure 3.7b). The HUASB reactors were UASB reactors (Armfield Anaerobic Digester W8) with some modifications inside the column. Plastic balls of 25 mm diameter were used as fixed film media.

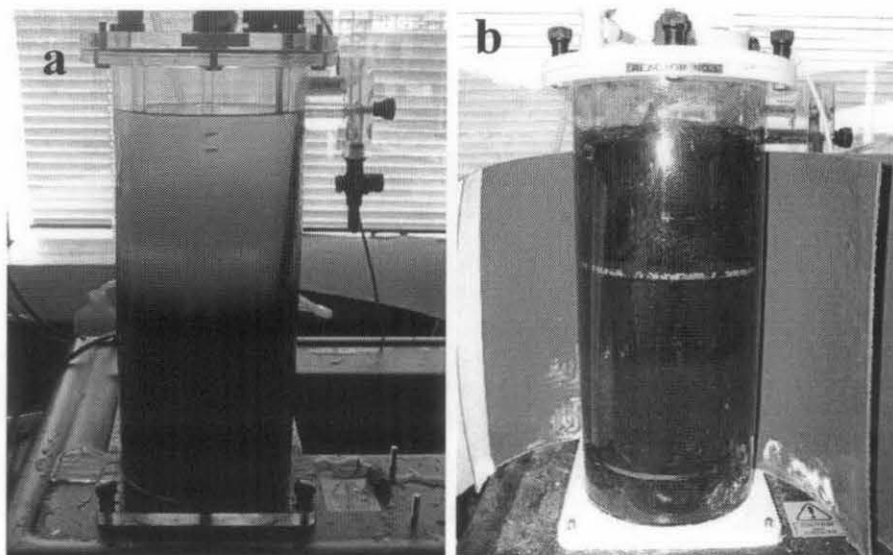


Figure 3.7 (a) UASB reactor and (b) HUASB reactor

3.2.4 Operation of the Reactors

The reactors were fed by pharmaceutical wastewater from a non-penicillin based product factory at Bangi, Malaysia without pre-treatment and dilution. Wastewater samples were collected every three to four weeks from a common sump by grab sampling. PVC containers were used to store wastewater in a cold room at 4°C before use. The stored wastewater was transferred to an influent tank daily for feed. The characteristics of the pharmaceutical wastewater are summarized in Table 3.2.

The UASB reactors were fed with low strength wastewater (COD 400-500 mg/L) for 75 days at HRTs of five and three days. From day 76 to day 170, it was then fed with high strength wastewater (COD 1773-2217 mg/L) at HRTs of five, four, three and two days.

The HUASB reactors were started 62 days after the UASB reactors. For the first 12 days of the operation of HUASB reactor, the reactors were fed with low strength wastewater at HRT of four days. On the day 13 of operation, the HUASB reactors were then fed with high strength wastewater at HRTs of five, four, three and two days.

Table 3.2 Characteristic of pharmaceutical wastewater (Phase II)

Parameter	Concentration (mg/L)
BOD ₅	299-1596
COD	458-2217
TSS	15-50
NH ₃ -N	2.5-29.3
NO ₃ -N	0.3-1.8
TKN	35.2-57.7
Total Phosphorus	4.8-19.4
Alkalinity	309-377
pH	4.76-6.04

3.2.5 Seed Biomass

The seed biomass was obtained from a sludge thickener of the activated sludge process based sewage treatment plant (STP) at the Universiti Teknologi PETRONAS (UTP), Malaysia. The TVSS concentrations after seeding were measured as 16277 mg/L and 17335 mg/L in UASB and HUASB reactors, respectively. Activated sludge was chosen to seed the UASB reactor because of the validity of such sludge as seed for anaerobic reactor (Kim and Speece, 2002).

The reactors were inoculated with 2.5 L of sludge. In order to acclimatize the sludge with pharmaceutical wastewater, the reactors were batch feed with 2.5 L of pharmaceutical wastewater (COD 400-500 mg/L) for 14 days and with continuous flow for 14 days. The acclimation period allows reduction of oxygen levels to prevent inhibition of anaerobic bacteria as well as for the bacteria population to adjust to the feed wastewater.

3.3 Analytical Methods

3.3.1 Measurement of pH

The pH was measured with a Hach pH meter (Model Sension 4) using Platinum Series pH Electrode (Model 51910). The pH meter was calibrated with pH 4.0, 7.0 and 10.0 buffers.

3.3.2 Measurement of Alkalinity

Alkalinity was measured by Standard Methods Section 2320 B Titration Method (APHA, 2005). The pH value of 4.5 is suggested as the equivalence points for the corresponding alkalinity concentrations. The alkalinity analysis was performed using a properly calibrated auto titration (Metrohm 702 SM Titrino) at room temperature.

3.3.3 Measurement of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand 5 days (BOD₅)

COD was measured by the reactor digestion method (Method 8000) using Hach reagent kit (Hach, 2002). High range COD digestion reagent vials were used for this purpose. Colorimetric determination of COD was carried out at 620 nm using a Hach spectrophotometer DR 2000. BOD₅ was measured by Standard Methods Section 5210 B 5 Day BOD Test (APHA, 2005). Dissolved oxygen (DO) was measured using a YSI 5100 Dissolved Oxygen Meter.

3.3.4 Measurement of Total Suspended Solids (TSS) and Total Volatile Suspended Solids (TVSS)

TSS was determined according to the Standard Methods Section 2540 D Total Suspended Solids Dried at 103-105°C Method (APHA, 2005). For TVSS measurement, the residue from the TSS measurements was ignited to constant weight at 550°C in the muffle furnace (Nabertherm L15/12/P320) according to Standard Methods Section 2540 E Fixed and Volatile Solids Ignited at 550°C Method (APHA, 2005). Mixed Liquor Suspended Solids (MLSS) was measured by TSS

method and Mixed Liquor Volatile Suspended Solids (MLVSS) was measured by TVSS method with proper dilution.

3.3.5 Measurement of Ammonia Nitrogen ($\text{NH}_3\text{-N}$), Nitrate Nitrogen ($\text{NO}_3\text{-N}$) and Total Phosphorus (TP)

$\text{NH}_3\text{-N}$ was measured by Nessler Method (Method 8038), $\text{NO}_3\text{-N}$ by Cadmium Reduction Method (Medium Range) using Hach Powder Pillow and TP by PhosVer 3 (Ascorbic Acid) Method using Hach Powder Pillow (Hach, 2002).

3.3.6 Measurement of Total Kjeldahl Nitrogen (TKN)

The macro-kjeldahl method was applied to measure TKN according to Standard Methods Section 4500- N_{org} B Macro-Kjeldahl Method (APHA, 2005). For digestion, Buchi K-424 Digestion Unit and Buchi B-414 Scrubber Unit were used, whereas for distillation, Buchi K-314 Distillation Unit was used. Selenium catalyst tablets were used in TKN measurement. For ammonia nitrogen measurement, Standard Methods Section 4500 C Titrimetric Method (APHA, 2005) was used. Titration was performed using a properly calibrated auto titration (Metrohm 702 SM Titrino) at room temperature.

3.3.7 Measurement of Volatile Fatty Acids (VFA)

VFA was measured by esterification method (Method 8196) using a DR 2000 spectrophotometer (Hach, 2002). The sample was centrifuged by Heraeus Biofuge Primo before it was analyzed. All volatile acids present are reported as their equivalent mg/L as acetic acid (HOAC).

3.3.8 Measurement of Methane Gas Production

Methane production was monitored by liquid displacement. The top of each reactor was connected to a gas tank for gas collection. The displacement liquid was a 5% NaOH solution with thymol blue as indicator. NaOH was chosen because it absorbs CO_2 and allows CH_4 to pass through it. The blue colour of indicator will be discharged when the CO_2 absorption capacity of the solution is exhausted

(Isa et al., 1993; Leitaó, 2004). However, the methane production data was not included in the results and discussion because there appeared to be some faults with the gas collection system. The methane production was only about 50% of the theoretical values based on stoichiometry calculation (350 mL CH₄/g COD).

3.4 Data Analysis

Statistical analysis, analysis of variance (ANOVA) was applied to the data obtained from the different reactors and in different operation condition in order to assess cause distinct effects on the performance of the reactors. One-way and two-way ANOVA were used to determine the significant difference between data that were obtained from each variable of the experiments.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Phase I Results: Treatment of Pharmaceutical Wastewater using Semi-anaerobic and Aerobic Reactors

The Phase I study was conducted to observe the performance of semi-anaerobic and aerobic system treating non-penicillin pharmaceutical wastewater. The study was performed using a semi-anaerobic baffled reactor (SABR) and two activated sludge process (ASP) reactors. The reactors were divided into two trains; Train 1 (SABR-ASP reactor) and Train 2 (ASP reactor). The performance of each reactor was evaluated in terms of COD and BOD₅ removal efficiencies. The nutrients and biomass in the reactors were also monitored.

4.1.1 COD and BOD₅ in Semi-anaerobic and Aerobic Reactors

The COD removal and COD concentration in Phase I are shown in Figure 4.1 and Figure 4.2, respectively and the overall COD removal in Train 1 and Train 2 is shown in Figure 4.3. For the first ten days, the influent COD concentration varied from 1853 to 1953 mg/L. The COD removal ranged from 86 to 93% and the effluent COD concentration varied from 142 to 265 mg/L in SABR. The Train 1 ASP reactor that received wastewater from the SABR achieved COD removal of 33-82%. Furthermore, the overall COD removals ranged from 95 to 98% and 81 to 89% for Train 1 and Train 2, respectively. The final COD concentrations varied from 45 to 96 mg/L and 207 to 364 mg/L for Train 1 and Train 2, respectively.

From day 11 to day 28, the influent COD concentration varied from 791 to 987 mg/L. The COD removal ranged from 71 to 92% and the effluent COD concentration varied from 70 to 246 mg/L in SABR. The Train 1 ASP reactor achieved a COD removal of 31-72%. The overall COD removals ranged from 90 to 94% and 85 to 92% for Train 1 and Train 2, respectively. The final COD concentrations varied from 48 to 102 mg/L and 66 to 140 mg/L for Train 1 and Train 2, respectively.

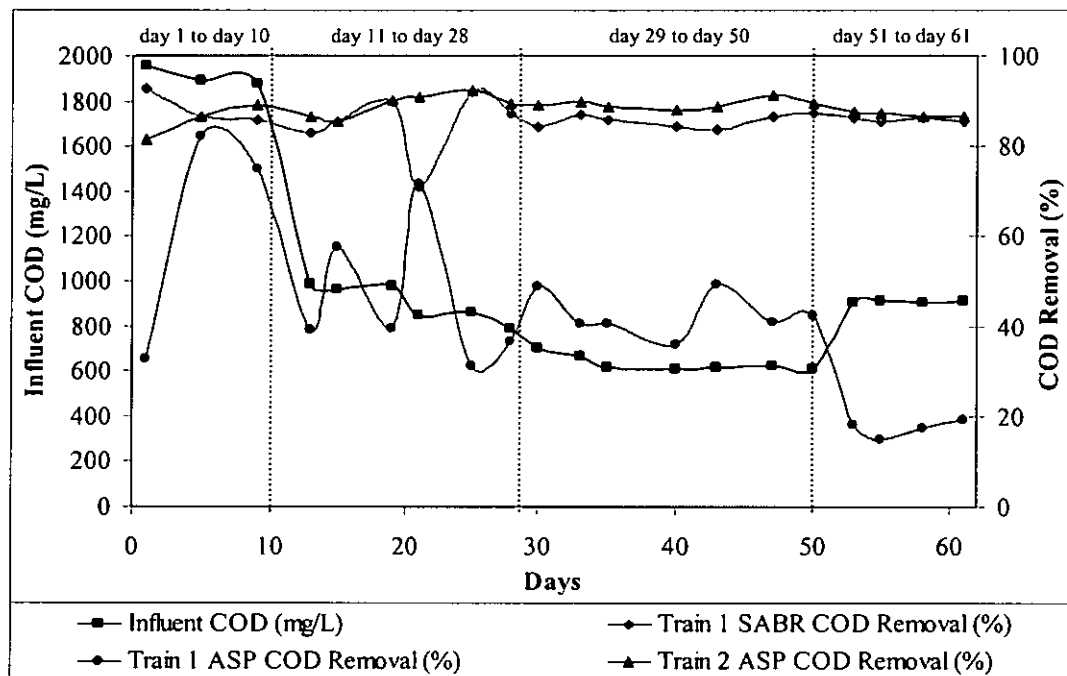


Figure 4.1 Phase I influent COD concentration and COD removal in the reactors

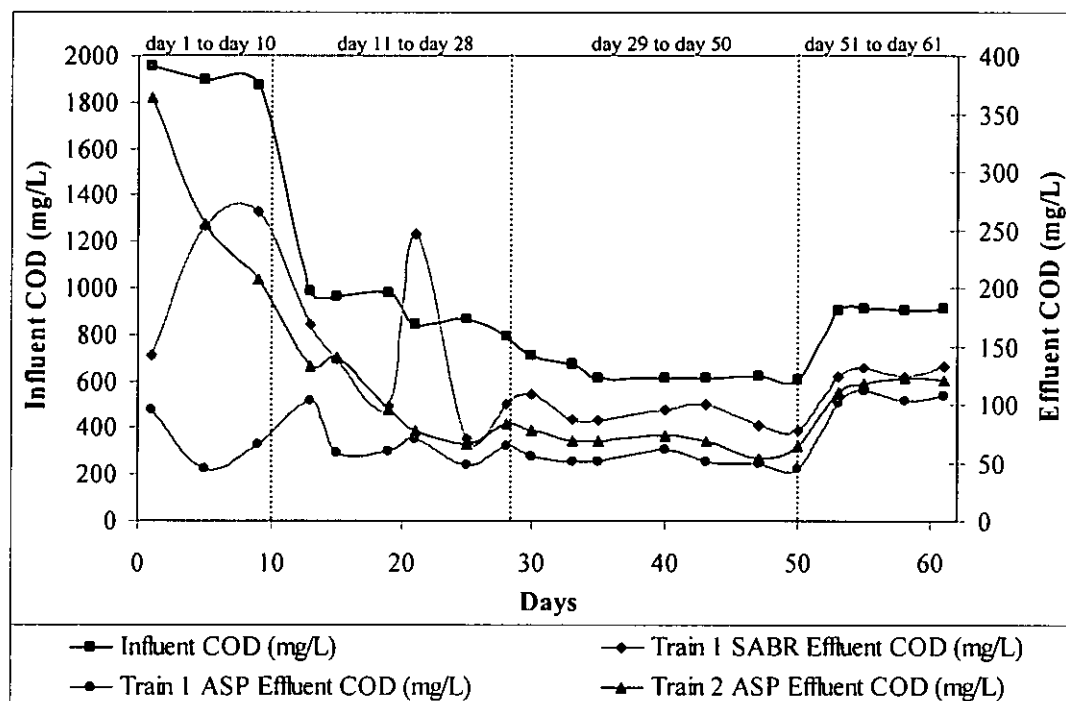


Figure 4.2 Phase I influent and effluent COD concentrations in the reactors

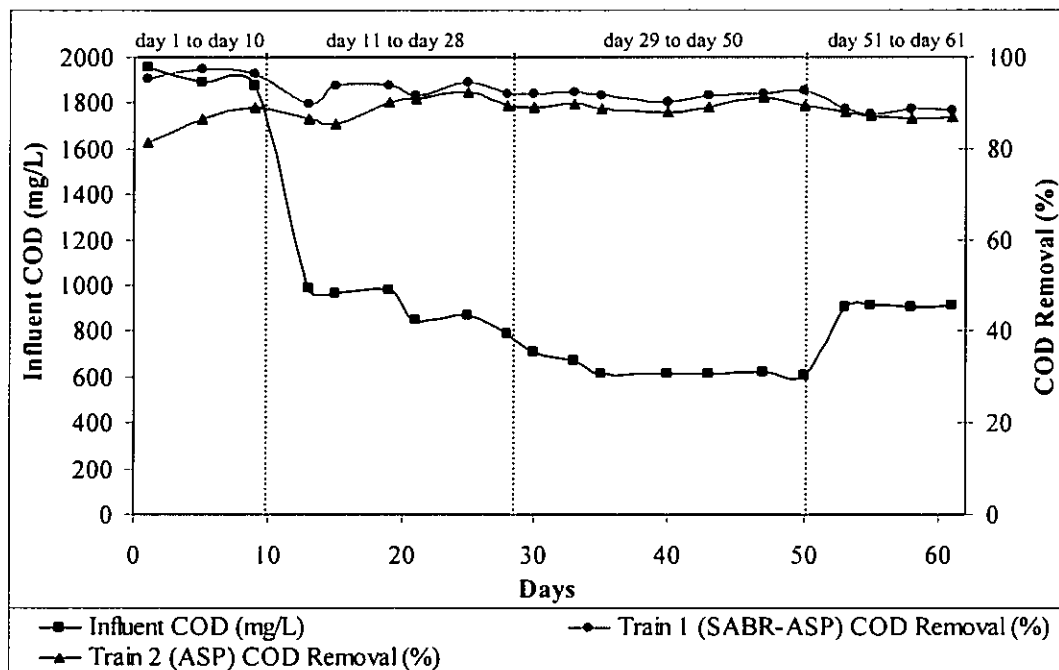


Figure 4.3 Influent COD concentration and Train 1 and Train 2 COD removal

From day 29 to day 50, the influent COD concentration ranged from 607 to 706 mg/L. The COD removal ranged from 84 to 87% in SABR, whereas the effluent COD concentration varied from 77 to 109 mg/L. The Train 1 ASP reactor achieved a COD removal of 36-49%. Furthermore, the overall COD removals ranged from 90 to 93% and 88 to 91% for Train 1 and Train 2, respectively. The final COD concentrations varied from 45 to 61 mg/L and 54 to 77 mg/L for Train 1 and Train 2, respectively.

For the last 11 days, the influent COD concentration varied from 905 to 913 mg/L. The COD removal ranged from 85 to 86% and the effluent COD concentration varied from 124 to 133 mg/L in SABR. The Train 1 ASP reactor achieved a COD removal of 15-19%. The overall COD removals ranged from 88 to 89% and 87 to 88% for Train 1 and Train 2, respectively. The final COD concentrations varied from 102 to 112 mg/L and 110 to 122 mg/L for Train 1 and Train 2, respectively.

The performance of each reactor was also evaluated in terms of the BOD₅ concentration. The BOD₅ removal and BOD₅ concentration in Phase I are shown in Figure 4.4 and Figure 4.5, respectively and the overall BOD₅ removal in Train 1 and Train 2 is shown in Figure 4.6. For the first ten days, the average influent BOD₅ concentration was 1299 mg/L. The average BOD₅ removal was 83% and the average effluent BOD₅ concentration was 225 mg/L in SABR. The Train 1 ASP reactor that received wastewater from the SABR achieved an average BOD₅ removal of 85%. Furthermore, the overall BOD₅ removals were 97% and 83% for Train 1 and Train 2, respectively. The final BOD₅ concentrations were 34 mg/L and 226 mg/L for Train 1 and Train 2, respectively. From day 11 to day 28, the influent BOD₅ concentration varied from 588 to 717 mg/L. The BOD₅ removal ranged from 66 to 85% and the effluent BOD₅ concentration varied from 70 to 246 mg/L in SABR. The Train 1 ASP reactor achieved a BOD₅ removal of 66-85%. The overall BOD₅ removals ranged from 89 to 92% and 84 to 89% for Train 1 and Train 2, respectively. The final BOD₅ concentrations varied from 48 to 77 mg/L and 69 to 118 mg/L for Train 1 and Train 2, respectively.

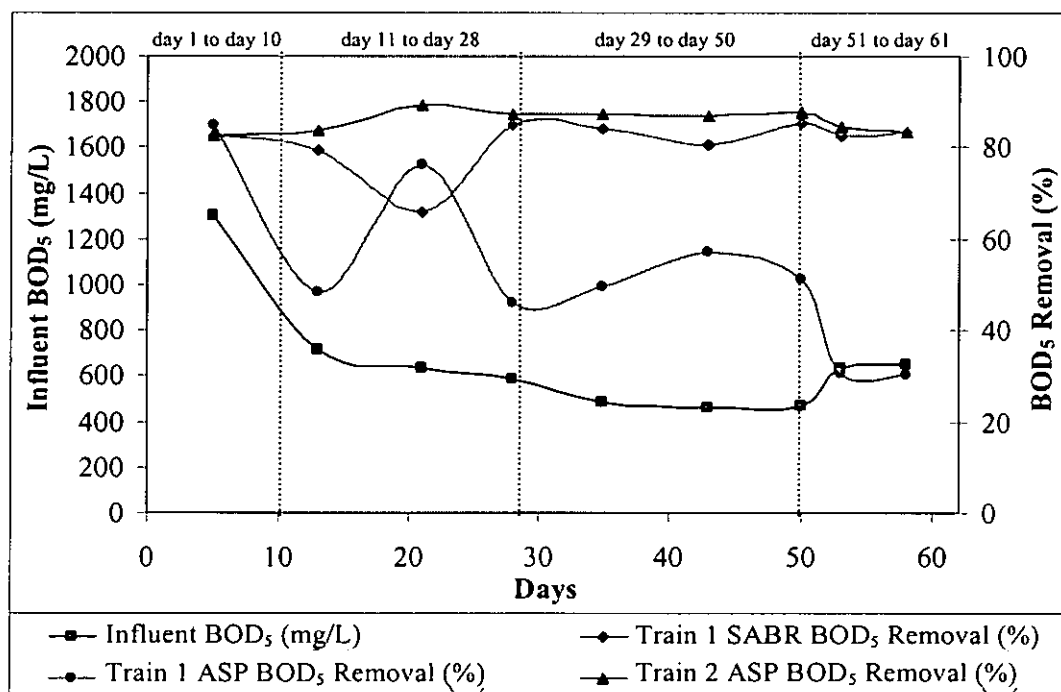


Figure 4.4 Phase I Influent BOD₅ concentration and BOD₅ removal in the reactors

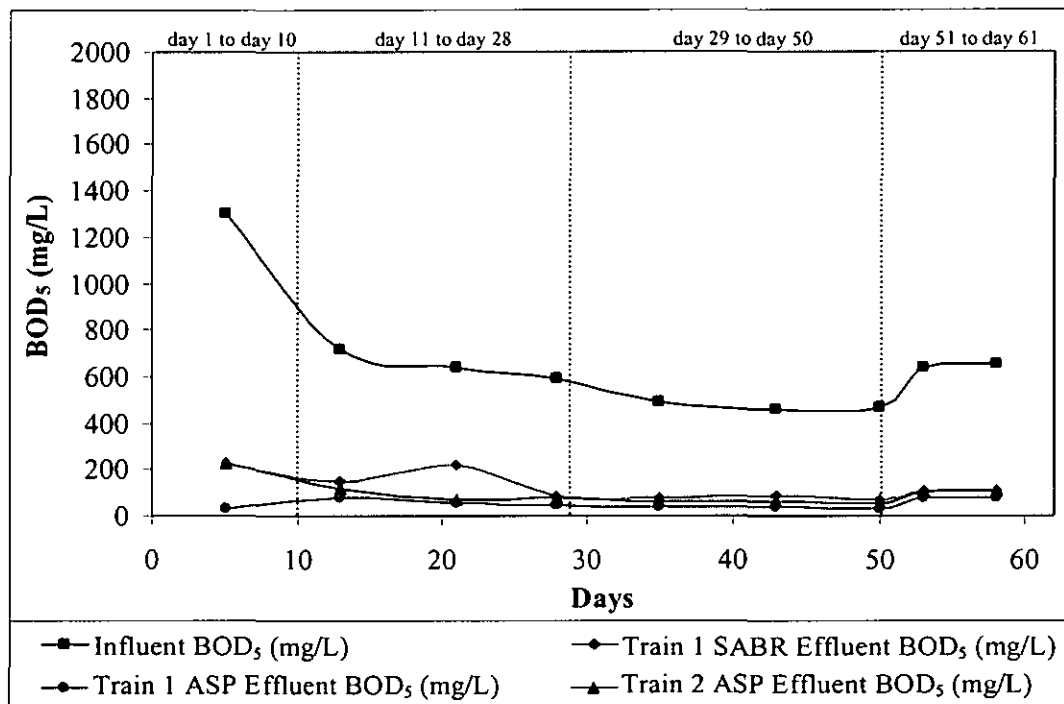


Figure 4.5 Phase I influent and effluent BOD₅ concentrations in the reactors

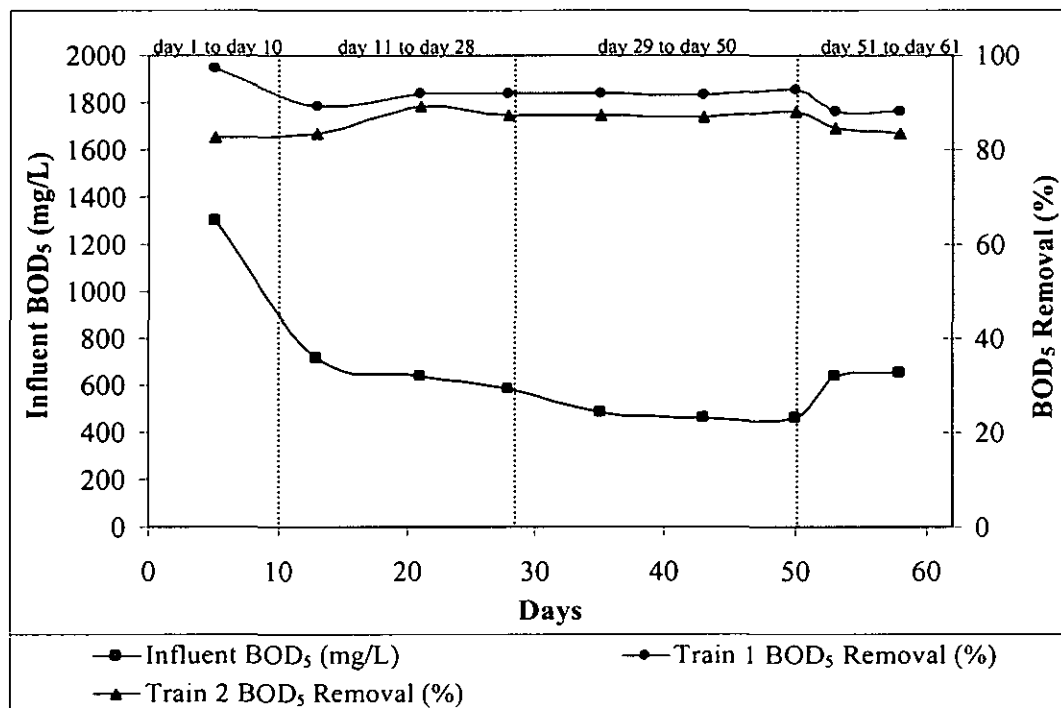


Figure 4.6 BOD₅ removal in Train 1 and Train 2

From day 29 to day 50, the influent BOD₅ concentration varied from 462 to 487 mg/L. The BOD₅ removal ranged from 81 to 85% and the effluent BOD₅ concentration varied from 69 to 89 mg/L in SABR. The Train 1 ASP achieved a BOD₅ removal of 50-57%. Furthermore, the overall BOD₅ removals ranged from 92 to 93% and 87 to 88% for Train 1 and Train 2, respectively. The final BOD₅ concentrations varied from 33 to 39 mg/L and 56 to 61 mg/L for Train 1 and Train 2, respectively.

For the last 11 days, the average influent BOD₅ concentration was 645 mg/L. The average BOD₅ removal was 83% and the average effluent BOD₅ concentration was 88 mg/L in SABR. The Train 1 ASP reactor achieved average BOD₅ removal of 30%. The average BOD₅ removals were 88% and 84% for Train 1 and Train 2, respectively. The average final BOD₅ concentrations were 77 mg/L and 103 mg/L for Train 1 and Train 2, respectively.

4.1.2 Total Suspended Solids (TSS) Analysis

In the 61 days, the reactors were fed with influent TSS concentration of 7-38 mg/L. The influent and effluent TSS concentrations during Phase I are shown in Figure 4.7. The effluent TSS concentration in SABR ranged from 18 to 58 mg/L while effluent TSS concentrations of 12-31 mg/L and 17-31 mg/L were found in Train 1 ASP reactor and Train 2 ASP reactor, respectively. The TSS concentrations increased because the settling sections of the reactors were not enough to settle the TSS. However, the effluent TSS concentrations in both ASP reactors were still low (less than 50 mg/L)

4.1.3 Mixed Liquor Suspended Solid (MLSS) and Sludge Retention Time (SRT)

In the acclimatisation period, approximately 0.5 L of mixed liquor was wasted daily to maintain a MLSS of 2000-4000 mg/L. Based on calculation, the SRT was approximately 38.4 days. During the 61 days, the MLSS concentration in Train 1 ASP reactor was lower than in Train 2 ASP reactor. Figure 4.8 shows the profile of

MLSS concentration and SRT during this study. In Train 1, the MLSS concentration varied from 2000 to 4367 mg/L while in Train 2, the MLSS concentration varied from 3083 to 5250 mg/L. The actual SRT varied from 32.35 to 36.81 days and 33.36 to 36.45 days for Train 1 ASP reactor and Train 2 ASP reactor, respectively.

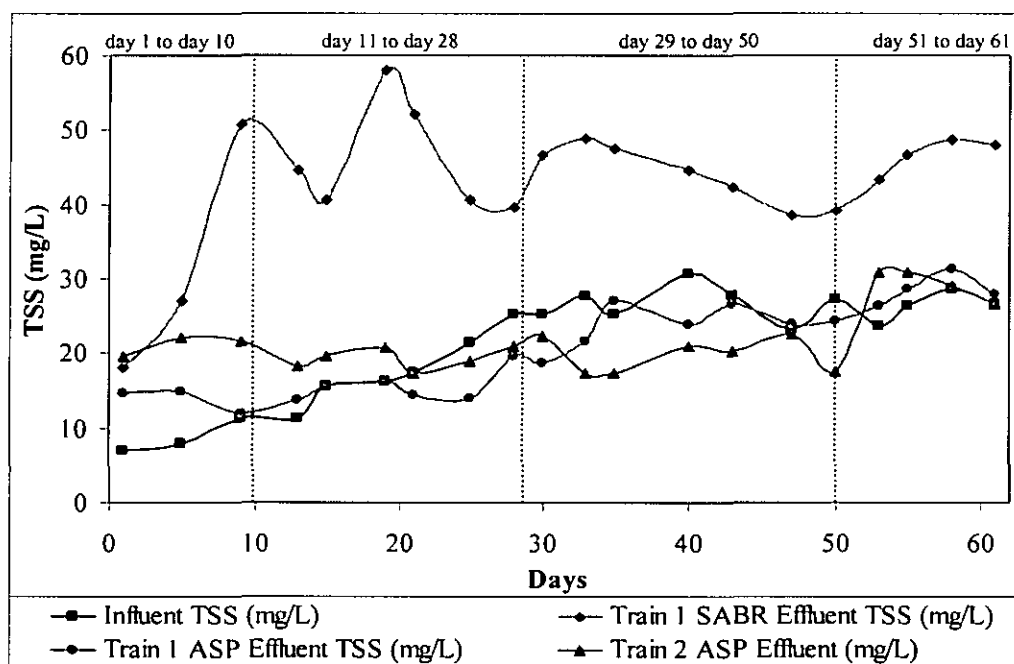


Figure 4.7 Phase I influent and effluent TSS concentrations in the reactors

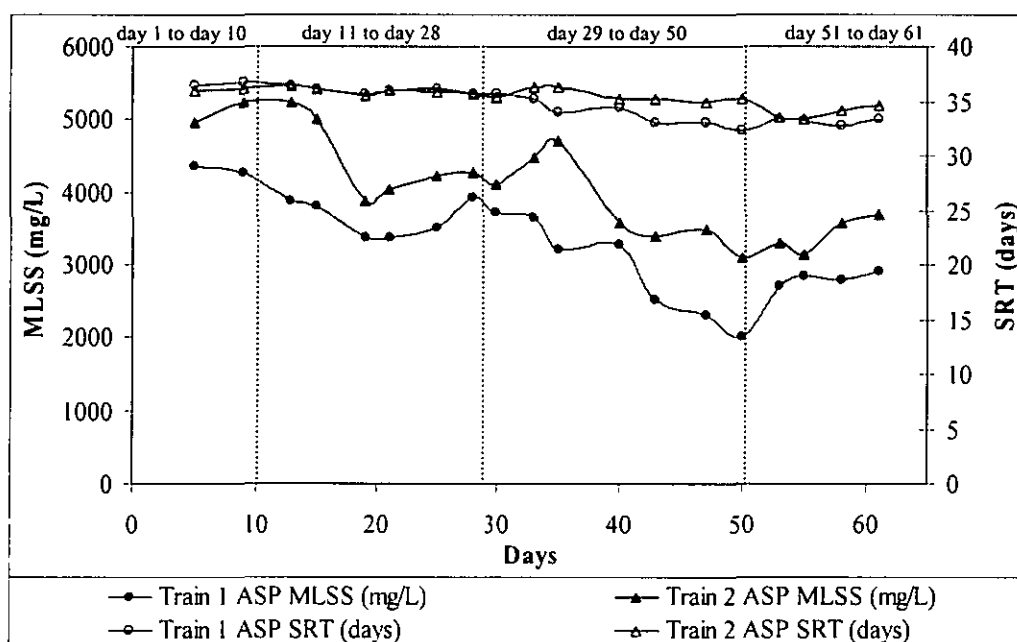


Figure 4.8 Phase I MLSS concentration and SRT in ASP reactors

4.1.4 Mixed Liquor Volatile Suspended Solid (MLVSS) and Food to Microorganism Ratio (F/M Ratio)

In the 61 days, the Train 1 ASP reactor was fed with influent BOD_5 of 69-225 mg/L while the Train 2 ASP reactor was fed with influent BOD_5 of 462-1299 mg/L. The MLVSS in ASP reactors ranged from 1100 to 2517 mg/L and 1850 to 3567 mg/L for Train 1 and Train 2, respectively. Based on calculations, the F/M ratios in ASP reactors ranged from 0.02 to 0.05 g BOD_5 /g MLVSS and 0.07 to 0.19 g BOD_5 /g MLVSS for Train 1 and Train 2, respectively. The F/M ratio of Train 1 ASP reactor was lower than the F/M ratio of the Train 2 ASP reactor because former received partially treated wastewater from the SABR. The lower F/M ratio also resulted in the lower concentration of biomass in Train 1 ASP reactor. The MLVSS concentrations varied in accordance with the organic content of the pharmaceutical wastewater. The MLVSS concentrations and F/M ratios in ASP reactors during the Phase I study are shown in Figure 4.9.

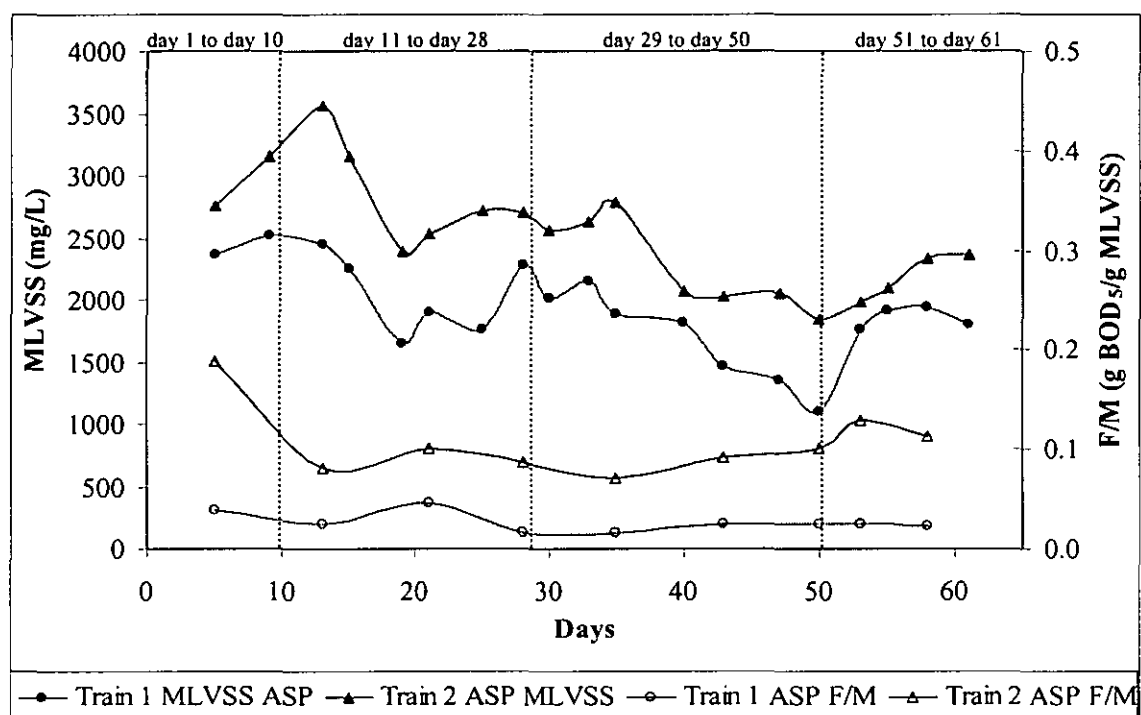


Figure 4.9 Phase I MLVSS concentration and F/M ratio in ASP reactors

4.1.5 Nutrients Analysis

Figure 4.10 to Figure 4.14 show the influent and effluent nutrient concentrations ($\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$ and TP) in Phase I. For the first ten days, the influent $\text{NH}_3\text{-N}$ concentration ranged from 22.6 to 24.8 mg/L. The $\text{NH}_3\text{-N}$ removal ranged from 46 to 52% and the effluent $\text{NH}_3\text{-N}$ concentration varied from 11.4 to 13.4 mg/L in SABR. The Train 1 ASP reactor that received wastewater from the SABR achieved a $\text{NH}_3\text{-N}$ removal of 69-74%. Furthermore, the overall $\text{NH}_3\text{-N}$ removals ranged from 85 to 86% and 78 to 80% for Train 1 and Train 2, respectively. The final $\text{NH}_3\text{-N}$ concentrations ranged from 3.2 to 3.5 mg/L and 4.65 to 5.32 mg/L for Train 1 and Train 2, respectively. The influent TP concentration ranged from 3.03 to 3.63 mg/L. The TP concentrations in SABR slightly decreased with effluent TP of 1.66-2.98 mg/L. The Train 1 ASP reactor that received wastewater from the SABR achieved the TP removal of 36-49%. The overall TP removals ranged from 49 to 65% and 36 to 46% for Train 1 and Train 2, respectively. The final TP concentrations ranged from 1.07 to 1.86 mg/L and 1.78 to 1.97 mg/L for Train 1 and Train 2, respectively.

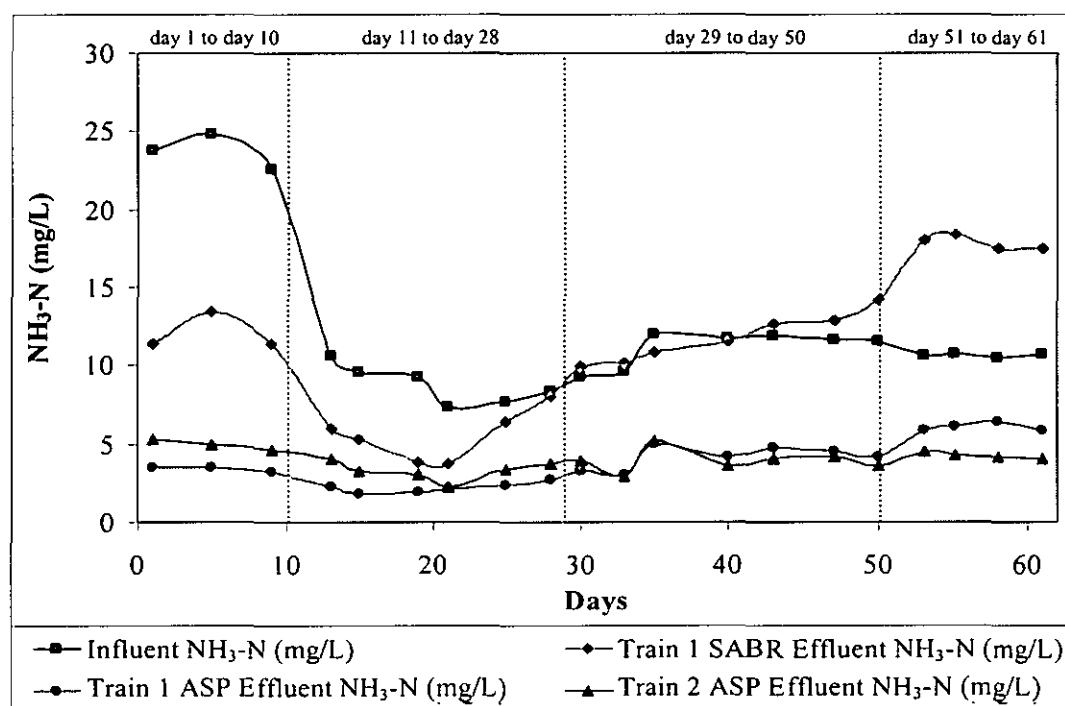


Figure 4.10 Phase I influent and effluent $\text{NH}_3\text{-N}$ concentrations in the reactors

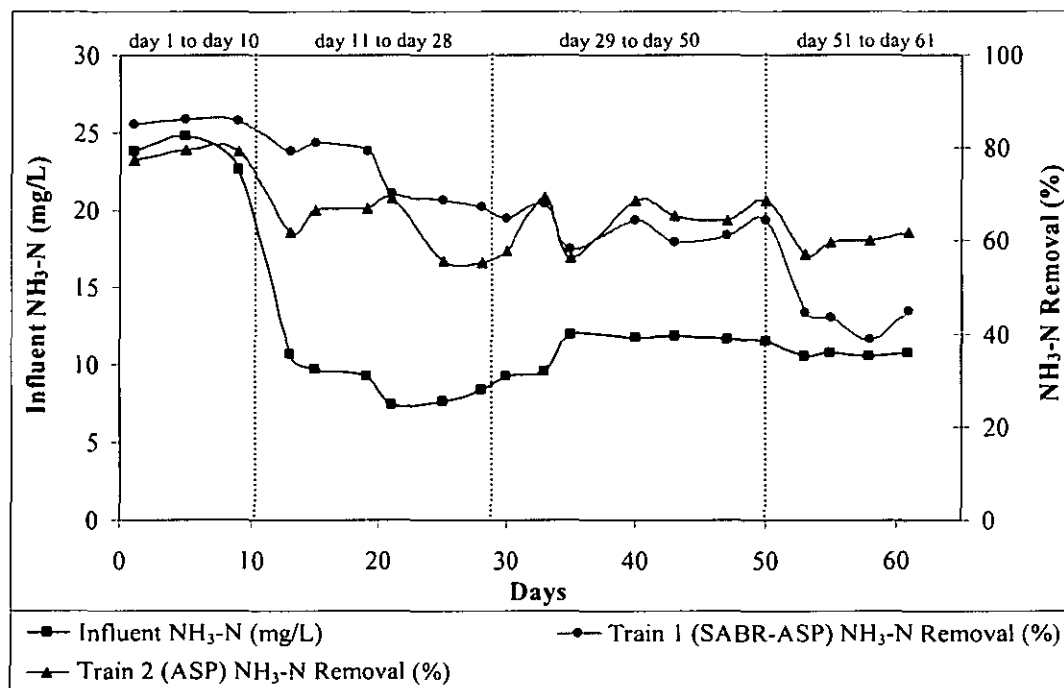


Figure 4.11 Influent $\text{NH}_3\text{-N}$ concentration and $\text{NH}_3\text{-N}$ removal in Train 1 and Train 2

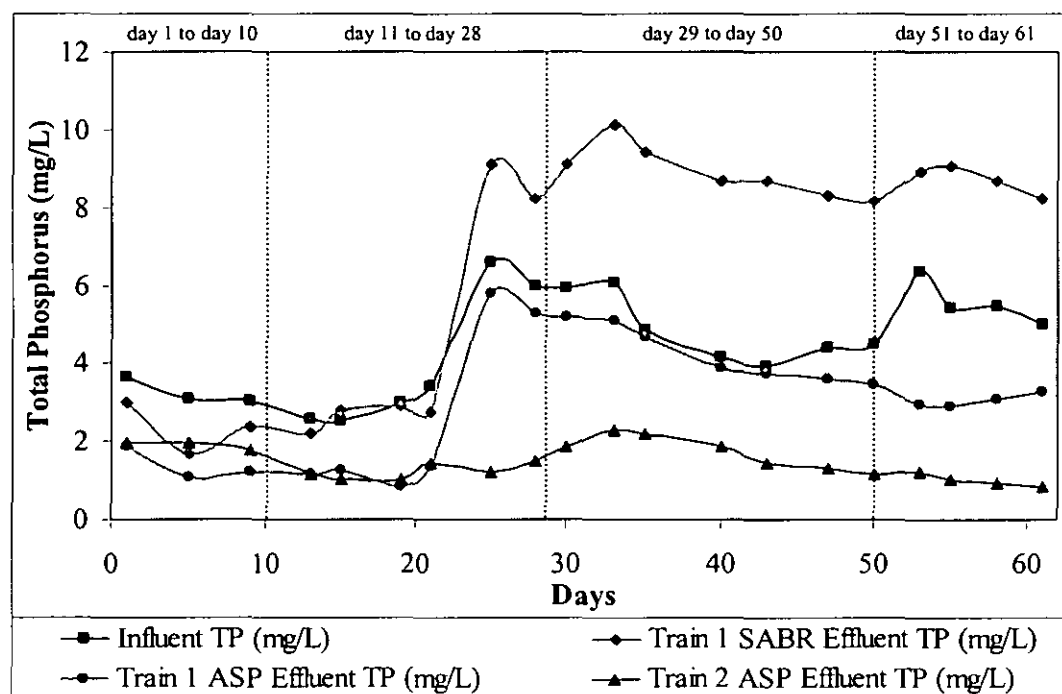


Figure 4.12 Phase I influent and effluent TP concentrations

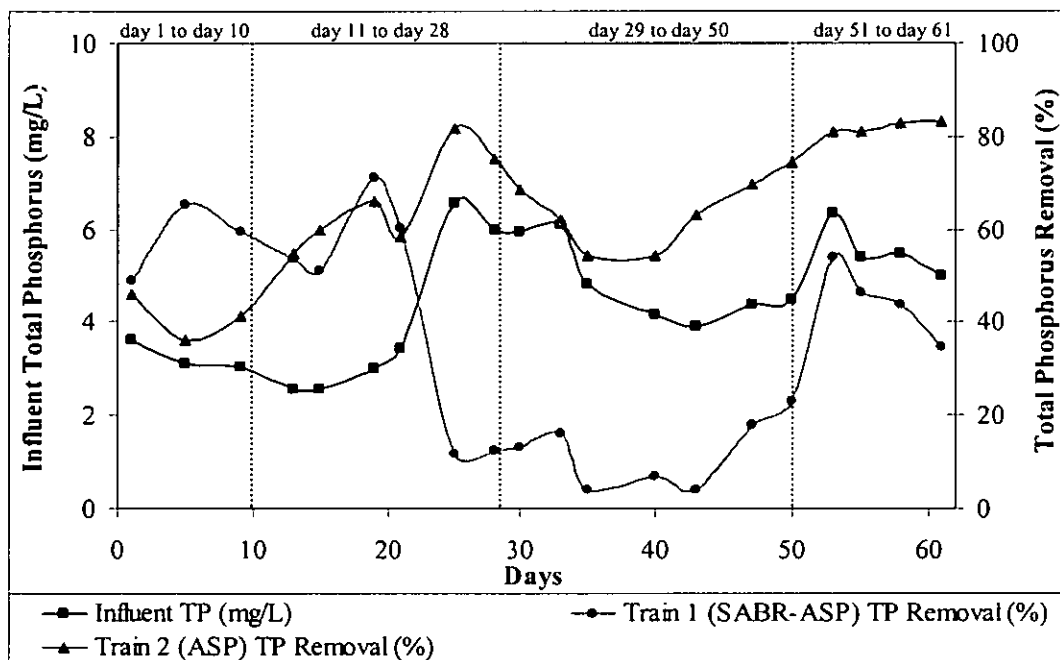


Figure 4.13 Influent TP concentration and TP removal in Train 1 and Train 2

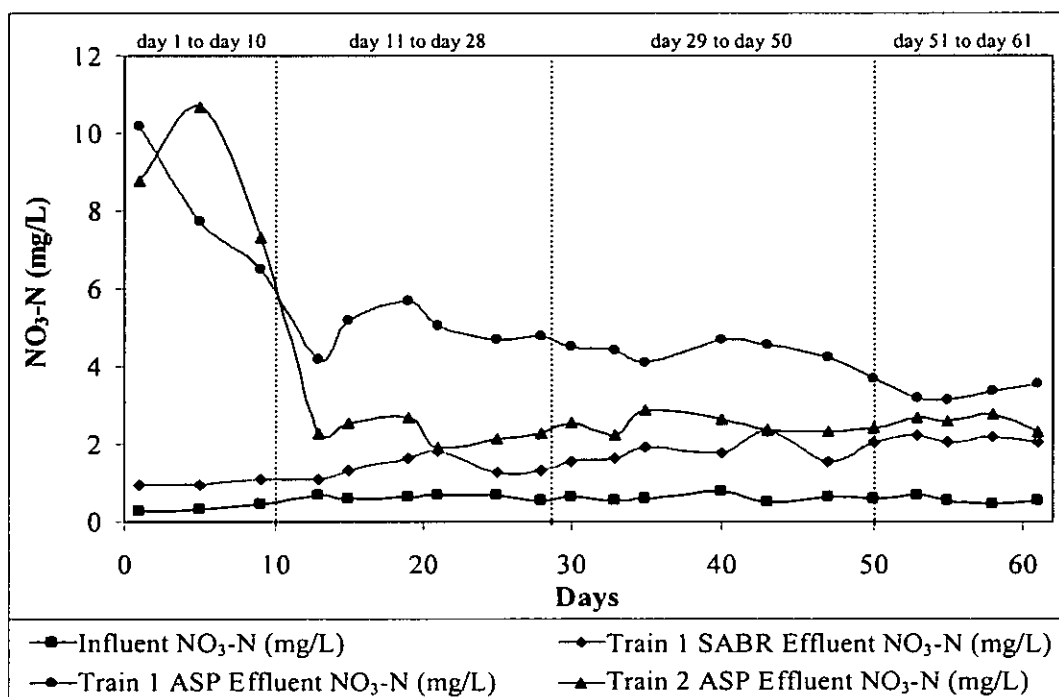


Figure 4.14 Phase I influent and effluent $\text{NO}_3\text{-N}$ concentrations in the reactors

From day 11 to day 28, the influent $\text{NH}_3\text{-N}$ concentration was lower than the influent at the first ten days. The influent $\text{NH}_3\text{-N}$ concentration ranged from 7.4 to 10.6 mg/L. The $\text{NH}_3\text{-N}$ removal ranged from 3 to 59% and the effluent $\text{NH}_3\text{-N}$ concentration varied from 3.7 to 8.0 mg/L in SABR. The Train 1 ASP reactor achieved the $\text{NH}_3\text{-N}$ removal of 42-66%. The overall $\text{NH}_3\text{-N}$ removals ranged from 68 to 81% and 55 to 69% for Train 1 and Train 2, respectively. The final $\text{NH}_3\text{-N}$ concentrations ranged from 1.80 to 2.70 mg/L and 2.27 to 4.02 mg/L for Train 1 and Train 2, respectively. The influent TP concentration ranged from 2.54 to 6.57 mg/L. The TP concentrations in SABR slightly increased with effluent TP of 2.18-9.10 mg/L. The Train 1 ASP reactor achieved the TP removal of 36-70%. Furthermore, the overall TP removals ranged from 12 to 72% and 55 to 82% for Train 1 and Train 2, respectively. The final TP concentrations ranged from 0.86 to 5.81 mg/L and 1.02 to 1.50 mg/L for Train 1 and Train 2, respectively.

From day 29 to day 50, the influent $\text{NH}_3\text{-N}$ concentration was similar with the influent at the last eleven days. From day 29 to day 50, the influent $\text{NH}_3\text{-N}$ concentrations ranged from 9.3 to 11.9 mg/L whereas at the last eleven days, the influent $\text{NH}_3\text{-N}$ concentration ranged from 10.5 to 10.8 mg/L. The $\text{NH}_3\text{-N}$ concentration at SABR increased and the effluent $\text{NH}_3\text{-N}$ concentration varied from 9.9 to 18.4 mg/L. The Train 1 ASP reactor achieved a $\text{NH}_3\text{-N}$ removal of 54-71%. Furthermore, the overall $\text{NH}_3\text{-N}$ removals ranged from 59 to 68% and 56 to 69% for Train 1 and Train 2, respectively. The final $\text{NH}_3\text{-N}$ concentrations ranged from 3.07 to 6.43 mg/L and 2.93 to 5.20 mg/L for Train 1 and Train 2, respectively. From day 29 to day 50, the influent TP concentration ranged from 3.90 to 6.08 mg/L whereas it ranged from 5.00 to 6.33 mg/L for the last eleven days. The TP concentration at SABR increased and the effluent TP concentration varied from 8.17 to 10.12 mg/L. The Train 1 ASP reactor achieved a TP removal of 43-68%. The overall TP removals ranged from 4 to 54% and 55 to 83% were for Train 1 and Train 2, respectively. The final TP concentrations ranged from 2.90 to 5.16 mg/L and 0.84 to 2.31 mg/L for Train 1 and Train 2, respectively.

Under anaerobic conditions, phosphorus accumulating organisms (PAOs) will assimilate fermentation products (e.g. volatile fatty acids) into storage products within the cells with concomitant release of phosphorus from storage polyphosphates. Under aerobic conditions, energy is produced by the oxidation of storage products and polyphosphate storage within the cell increases (Metcalf & Eddy, 2003).

The average influent $\text{NO}_3\text{-N}$ concentration ranged from 0.3 to 0.8 mg/L. The result from all reactors showed that the $\text{NO}_3\text{-N}$ concentrations increased. The effluent $\text{NO}_3\text{-N}$ concentration in SABR varied from 0.9 to 2.3 mg/L. The final $\text{NO}_3\text{-N}$ concentrations ranged from 3.1 to 10.2 mg/L and 1.9 to 10.7 mg/L for Train 1 and Train 2, respectively. For the last 30 days, the effluent $\text{NH}_3\text{-N}$ concentration increased and the effluent $\text{NO}_3\text{-N}$ concentration was constant in SABR because nitrification did not occur.

4.2 Phase II Results: Treatment of Pharmaceutical Wastewater Using UASB and HUASB Reactors

In Phase II study, biological treatments were evaluated to treat non-penicillin pharmaceutical wastewater using UASB and HUASB reactors under mesophilic ($35\pm 2^\circ\text{C}$) and thermophilic ($55\pm 2^\circ\text{C}$) conditions. The reactors were fed with low strength and high strength influent at HRTs of five, four, three and two days. The performance of each reactor was evaluated in terms of COD and BOD_5 removals. The nutrients, VFA, alkalinity and pH in the reactors were also monitored.

4.2.1 COD and BOD_5 in Mesophilic and Thermophilic UASB Reactors

In the first 13 days, the reactors were fed with influent COD concentration of 458-499 mg/L at HRT of five days. The COD concentration in UASB reactors during this study is shown in Figure 4.15 and the UASB reactors performance in this study is shown in Figure 4.16.

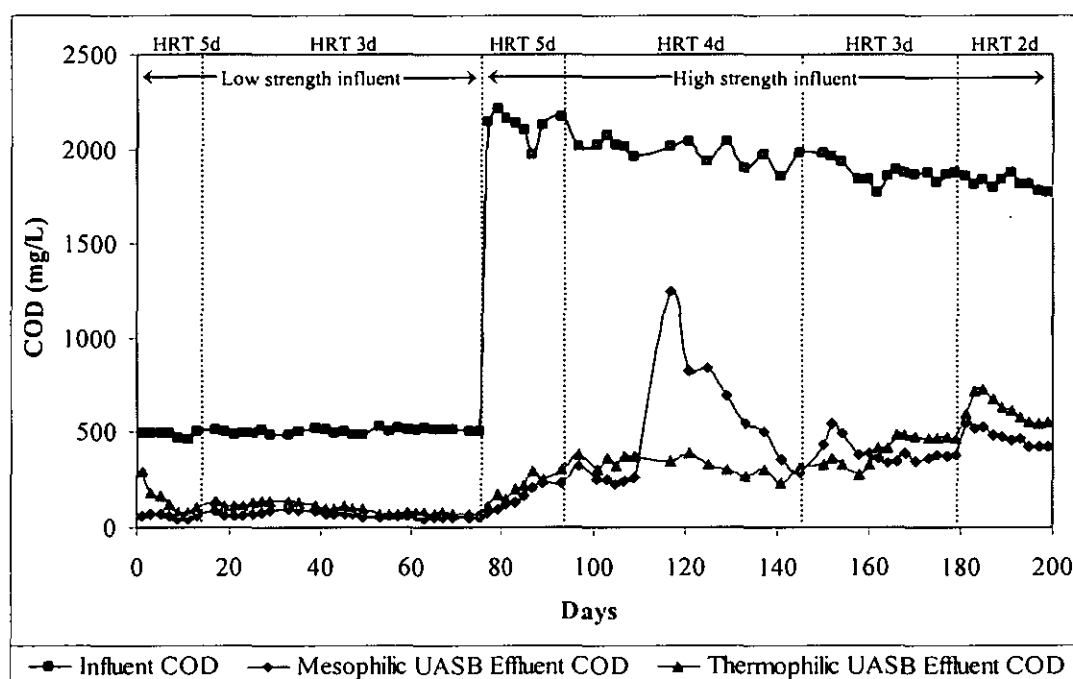


Figure 4.15 Influent and effluent COD concentrations in UASB reactors

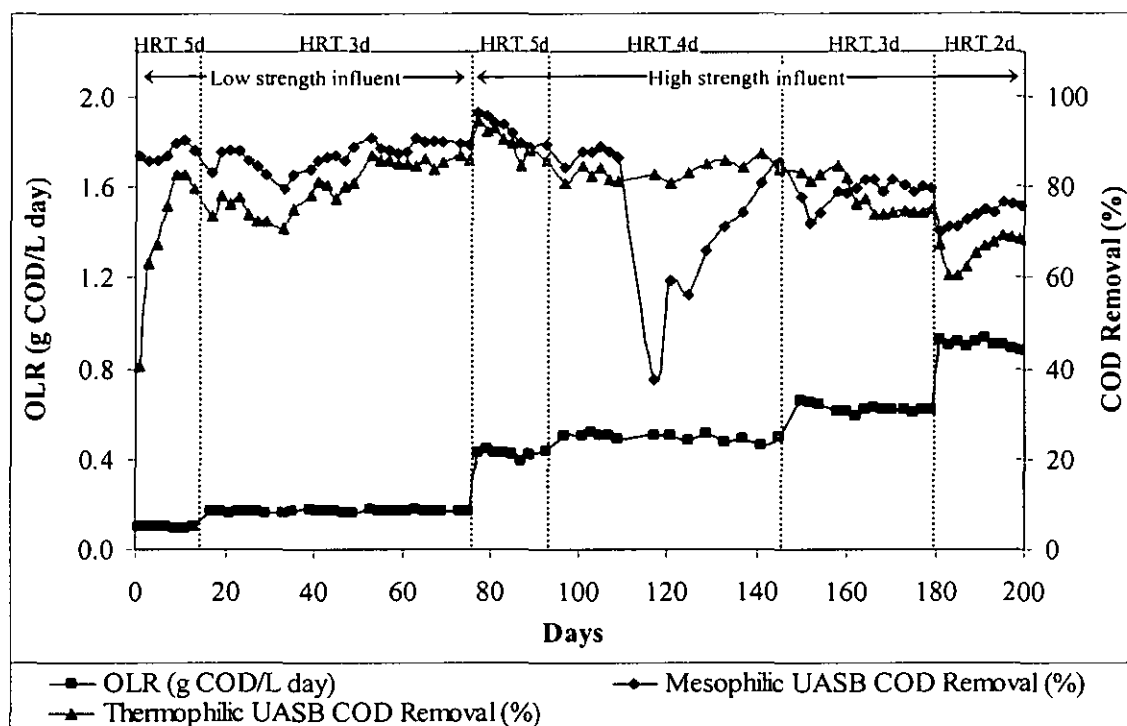


Figure 4.16 OLR and COD removal in UASB reactors

The mesophilic reactor reached steady state in the first week with effluent COD of 43-71 mg/L while the steady state of thermophilic reactor was reached after nine days with effluent COD of 78-101 mg/L. The COD removal efficiencies ranged from 86 to 91% and 80 to 83% for mesophilic and thermophilic UASB reactors, respectively. The average COD removal efficiencies and average effluent COD concentration at steady state condition in mesophilic UASB reactor were 88% and 60 mg/L, respectively and in thermophilic UASB reactor were 82% and 95 mg/L, respectively. Statistical analysis (ANOVA; $P < 0.05$) showed that COD removal was significantly higher at the mesophilic UASB reactor than at the thermophilic UASB reactor.

After 13 days, the HRT was decreased from five to three days. The UASB reactors were operated with average influent COD concentration of 505 mg/L. The organic loading rate (OLR) increased from 0.10 to 0.17 g COD/L-day at which the COD removals ranged from 80 to 91% and 71 to 87% for mesophilic and thermophilic UASB reactors, respectively. The removal efficiency of the mesophilic UASB

dropped slightly when the HRT of the reactor was reduced; however, that of the thermophilic UASB reactor decreased sharply and thereafter the efficiencies started to increase slowly in the following three weeks. The mesophilic UASB reactor reached steady state with average COD removal of 87% while the average COD removal of the thermophilic UASB reactor was 80%. The average effluent COD concentration at steady state was 65 mg/L and 83 mg/L for mesophilic and thermophilic UASB reactors, respectively. The mesophilic UASB reactor had higher COD removal than the thermophilic UASB reactor. A similar observation was also made by Chung (1997) in the treatment of a synthetic wastewater. The COD removals were found to be 83% and 76% in mesophilic and thermophilic UASB reactors, respectively (Chung, 1997). In present study, the mesophilic and thermophilic UASB reactors showed no significant change in COD removal (ANOVA; $P < 0.05$) as the HRT was decreased from five to three days with low strength pharmaceutical wastewater. Furthermore, at HRT of four days, COD removal was significantly greater at the mesophilic temperature than at the thermophilic temperature (ANOVA; $P < 0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From day 76, the UASB reactors were fed with high strength wastewater (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. The OLR increased from 0.39 to 0.94 g COD/L-day with the feed of high strength wastewater. The HRT was initially increased from three to five days to avoid shock loading in the reactors. From day 76 to day 93, the UASB reactors were operated at HRT of five days with influent COD concentration of 1970-2217 mg/L. Though the HRT was increased but the average OLR was still increased from 0.17 to 0.43 g COD/L-day due to the higher influent COD concentration of the wastewater collected from the factory. The COD removal efficiencies varied from 89 to 96% and 85 to 95% for mesophilic and thermophilic UASB reactors, respectively, while the effluent COD concentrations ranged from 76 to 234 mg/L and 115 to 305 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD removal efficiency of both UASB reactors increased rapidly, although the effluent COD concentration increased sharply in the two days. After four days, the COD removals were decreased slightly. The average COD removal efficiencies at steady state conditions were 93% and 90%

for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentration in mesophilic UASB reactor was 158 mg/L while that in thermophilic UASB reactor was 213 mg/L. The results indicated that the thermophilic UASB reactor was more stable worked with high strength wastewater, unlike the mesophilic reactor that was steady in both characteristics of wastewater. Furthermore, higher COD removal efficiencies were achieved by both reactors when treating a higher concentration wastewater at HRT of five days. The mesophilic and thermophilic UASB reactors showed a significantly higher COD removal (ANOVA; $P < 0.05$) as the HRT was increased from three to five days and as OLR increased due to the increase of COD concentration. However, the COD removal in mesophilic temperature at HRT of five days was not significantly difference from that at thermophilic temperature (ANOVA; $P < 0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From 94 day to day 145, the UASB reactors were operated at HRT of four days. The OLR increased from 0.43 to 0.50 g COD/L·day and the influent COD ranged from 1853 to 2073 mg/L. The COD removal decreased rapidly in both UASB reactors in four days because of COD shock loading, although, in the next four days the COD removal increased faintly. The COD removal efficiencies ranged from 81 to 89% and 81 to 87% for mesophilic and thermophilic UASB reactors, respectively. The effluent COD concentrations ranged from 225 to 353 mg/L and 237 to 386 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentrations and the percentage COD removals at steady state were 262 mg/L and 87% for mesophilic UASB reactor and 329 mg/L and 83% for thermophilic UASB reactor, respectively. Based on statistical analysis (ANOVA; $P < 0.05$), the COD removal at HRT of four days was significantly decreased if it was compared with the COD removal at HRT of five days for both UASB reactors.

On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The temperature increased to 60°C in one day and some sludge was washed out. From day 111 to day 118, the mesophilic UASB reactor was operated at ambient temperature ($24 \pm 2^\circ\text{C}$) while it was being repaired. The COD concentration

increased sharply from 260 to 1254 mg/L. The percentage removal in the reactor during the upset period was not included in data analysis. After 30 days, the reactor stabilized with COD effluent of 353 mg/L and the COD removal efficiency reached 81%.

Leitao et al. (2006) reviewed the effect of temperature shock on the anaerobic reactor performance. The anaerobic reactor operated under steady state conditions when it exposed to a sudden temperature change, the process could become unbalanced due to the different response of the various metabolic groups of microorganism. A temperature shock might cause an immediate pH drop in the anaerobic reactor. Then, it would stabilize at pH that was slightly lower than the previous steady state pH. This phenomenon was due to an increase of the VFA. The effluent COD increased due to the increase of effluent VFA and suspended solids concentrations (Leitao et al., 2006).

From day 146 to day 179, the UASB reactors were operated at HRT of three days with influent COD concentration of 1773-1977 mg/L. The COD removal efficiency of the mesophilic UASB dropped roughly in seven days from 85 to 72%, although it increased again in the next six days. It seems the reactor was still sensitive to organic loading due to its previous failure (temperature shock). In thermophilic UASB reactor, the COD removal efficiency decreased slightly in 16 days from 84 to 76%. The COD removal efficiencies varied from 72 to 82% and 74 to 85% for mesophilic and thermophilic UASB reactors, respectively, while the effluent COD concentrations ranged from 339 to 547 mg/L and 282 to 489 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average COD removal efficiencies at steady state conditions were 80% and 75% for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentration in mesophilic UASB reactor was 369 mg/L while in thermophilic UASB reactor was 464 mg/L. The mesophilic and thermophilic UASB reactors showed a significantly lower COD removal (ANOVA; $P < 0.05$) as the OLR increased due to HRT decrease from four to three days. The OLR increased from 0.59 to 0.66 g COD/L·day. Furthermore, the COD removal at the mesophilic temperature at HRT of three days was

significantly higher from that at the thermophilic temperature (ANOVA; $P < 0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

For the last 20 days, the UASB reactors were operated at HRT of two days. The average OLR was 0.91 g COD/L·day and the influent COD ranged from 1853 to 2073 mg/L. The COD removal decreased rapidly in both UASB reactors in two days because of COD shock loading, although, in the next two days the COD removal increased slightly in mesophilic UASB reactor from 70 to 71%, while in thermophilic UASB reactor the COD removal increased slightly in eight days from 60 to 65%. The COD removal efficiencies ranged from 70 to 76% and 60 to 69% for mesophilic and thermophilic UASB reactors, respectively. The effluent COD concentrations ranged from 424 to 553 mg/L and 549 to 726 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average effluent COD concentrations and the percentage COD removals at steady state were 478 mg/L and 74% for mesophilic UASB reactor and 582 mg/L and 68% for thermophilic UASB reactor, respectively. Based on statistical analysis (ANOVA; $P < 0.05$), COD removal at HRT of two days was significantly decreased compared to COD removal at HRT of three days in both UASB reactors. Moreover, the COD removal at the mesophilic temperature at HRT of two days was significantly higher from that at the thermophilic temperature (ANOVA; $P < 0.05$).

The performances of the UASB reactors were also evaluated based on BOD_5 . From day 1 to day 13, the reactor was fed with influent BOD_5 of 299-311 mg/L at HRT of five days. The influent and effluent BOD_5 concentrations during this study in UASB reactors are shown in Figure 4.17. The BOD_5 removal efficiencies ranged from 88 to 93% and 87 to 90% for mesophilic and thermophilic UASB reactors, respectively. The effluent BOD_5 concentrations were from 20 to 36 mg/L and 31 to 39 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average BOD_5 removal efficiency and average effluent BOD_5 concentration in mesophilic UASB reactor at steady state condition was 91% and 27 mg/L, respectively, while the average BOD_5 removal of 88% and average effluent BOD_5

concentration of 35 mg/L were achieved in thermophilic UASB reactor. The BOD_5 removal in UASB reactors during this study is shown in Figure 4.18.

The BOD_5/COD ratio of the pharmaceutical wastewater varied from 0.62 to 0.72. Even though the BOD_5 and COD concentrations of the wastewater were fluctuated a lot but the BOD_5/COD ratio was relatively constant. The average BOD_5 removal and BOD_5/COD ratio during this study in UASB reactors are shown in Figure 4.19. At HRT of five days, the BOD_5/COD ratio of the pharmaceutical wastewater that was fed to the UASB reactors was 0.62. After being treated by the UASB reactors, the BOD_5/COD ratios were 0.45 and 0.37 for mesophilic and thermophilic temperatures, respectively. The BOD_5/COD ratio in thermophilic UASB reactor was lower than in mesophilic UASB reactor. On the other hand, the performance of thermophilic UASB reactor was worse than the mesophilic reactor. From the observation, the degradation of organic matter in thermophilic UASB reactor was more dominantly influence by the degradation of biodegradable organic matter BOD_5 than COD.

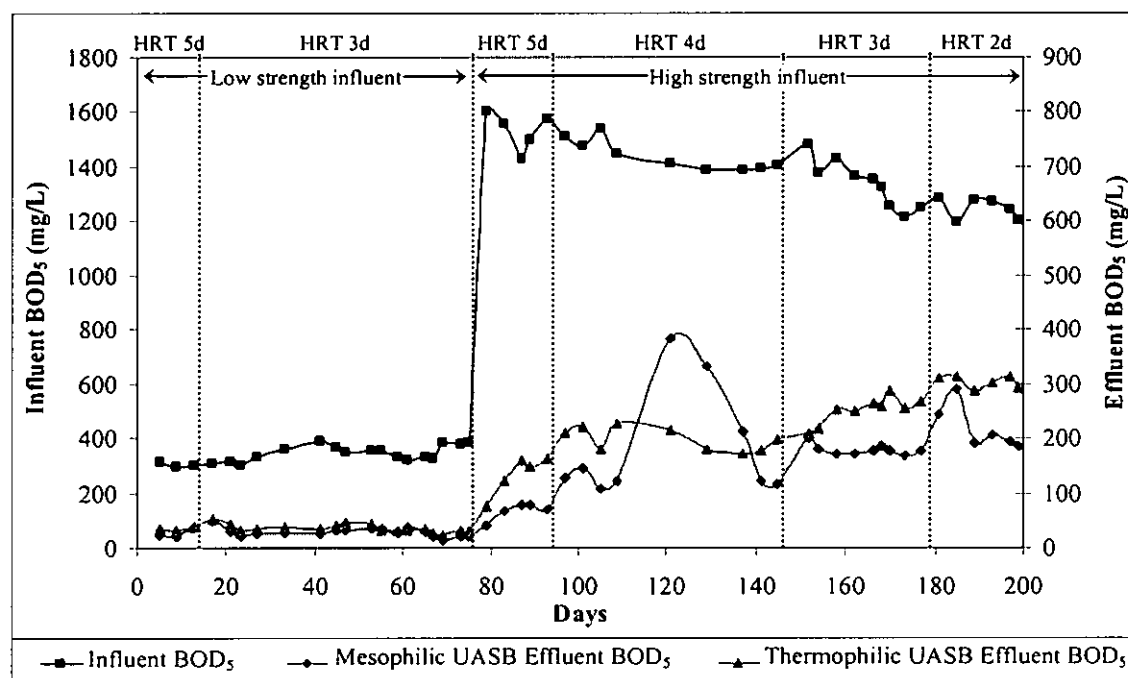


Figure 4.17 Influent and effluent BOD_5 concentrations in UASB reactors

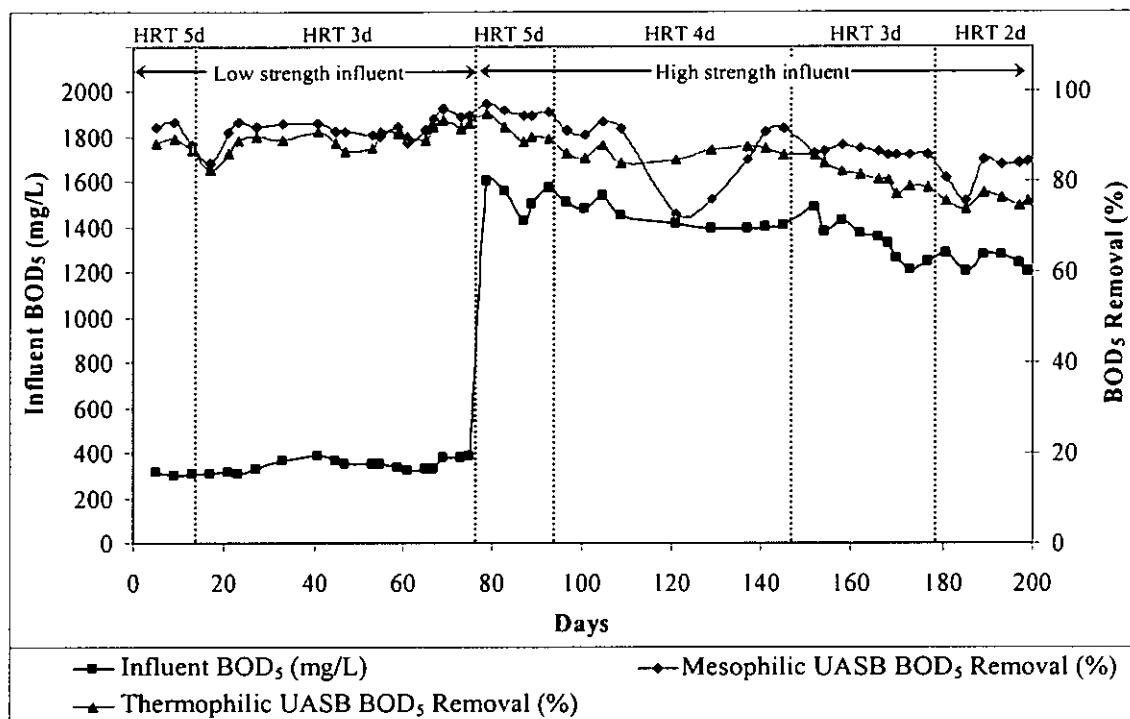


Figure 4.18 Influent BOD₅ concentration and BOD₅ removal in UASB reactors

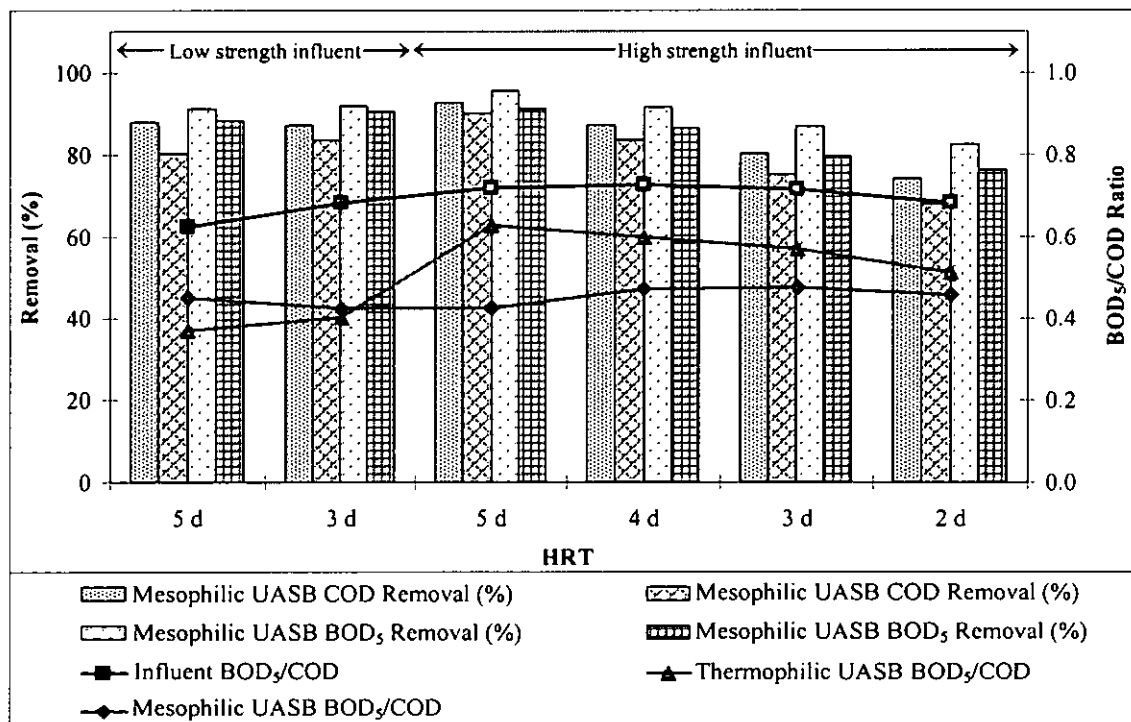


Figure 4.19 Average BOD₅ and COD removals and BOD₅/COD ratio in UASB reactors at steady state condition

After 13 days, the HRT was decreased from five to three days. The BOD₅ concentration ranged from 305 to 386 mg/L. The effluent concentrations were from 14 to 49 mg/L and 24 to 53 mg/L for mesophilic and thermophilic UASB reactors, respectively, while the BOD₅ removal efficiencies ranged from 84 to 96% and 83 to 94% for mesophilic and thermophilic UASB reactors, respectively. At steady state condition, the average effluent BOD₅ concentration and average BOD₅ removal were 28 mg/L and 92% respectively, in mesophilic UASB reactor and 34 mg/L and 90% respectively, in thermophilic UASB reactor. The influent BOD₅/COD ratio was 0.68 while the BOD₅/COD ratios of the mesophilic and thermophilic UASB reactors were 0.43 and 0.40, respectively.

From day 76, the UASB reactors were fed with high strength wastewater with BOD₅ concentration of 1198-1600 mg/L at HRTs of five, four, three and two days. The BOD₅/COD ratio of high strength pharmaceutical wastewater ranged from 0.68 to 0.72. From day 76 to day 93, the UASB reactors were operated at HRT of five days with BOD₅ concentration of 1427-1600 mg/L. The BOD₅ removal efficiencies varied from 95 to 97% and 89 to 95% for mesophilic and thermophilic UASB reactors, respectively, while the effluent BOD₅ concentrations ranged from 42 to 79 mg/L and 77 to 163 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average BOD₅ removal efficiencies at steady state conditions were 96% and 91% for mesophilic and thermophilic UASB reactors, respectively. The average effluent BOD₅ concentration in mesophilic UASB reactor was 67 mg/L while it was 134 mg/L in thermophilic UASB reactor. The BOD₅/COD ratio of pharmaceutical wastewater was 0.72 while the BOD₅/COD ratios of the mesophilic and thermophilic UASB reactors were 0.43 and 0.63, respectively.

From day 94 to day 145, the UASB reactors were operated at HRT of four days. The influent BOD₅ ranged from 1388 to 1540 mg/L and effluent BOD₅ ranged from 107 to 144 mg/L and 171 to 228 mg/L for mesophilic and thermophilic UASB reactors, respectively. The BOD₅ removal efficiencies ranged from 90 to 93% and 84 to 88% for mesophilic and thermophilic UASB reactors, respectively. The average effluent BOD₅ concentrations and percentage BOD₅ removals at steady state were

124 mg/L and 92% for mesophilic UASB reactor and 197 mg/L and 86% for thermophilic UASB reactor, respectively. The BOD₅/COD ratio of influent was 0.72 while the BOD₅/COD ratios of the mesophilic and thermophilic UASB reactors were 0.47 and 0.60, respectively. During the mesophilic UASB reactor breakdown period, the BOD₅ removal efficiency dropped from 92 to 73% while the BOD₅ concentration was 382 mg/L. After about a month, the mesophilic UASB stabilized at the BOD₅ removal of 92% and BOD₅ effluent concentration of 117 mg/L. Reactor performance during breakdown was not included in data analysis.

From day 146 to day 179, the UASB reactors were operated at HRT of three days with influent BOD₅ of 1212-1483 mg/L, while for the last 20 days, the UASB reactors were operated at HRT of two days with influent BOD₅ of 1198-1280 mg/L. The BOD₅ removal efficiencies in mesophilic UASB reactor varied from 86 to 88% and 76 to 85% for HRTs of three and two days, respectively, while the effluent concentrations ranged from 169 to 201 mg/L and 185 to 290 mg/L for HRTs of three and two days, respectively.

The BOD₅/COD ratios in mesophilic UASB reactor decreased from 0.71 to 0.48 and 0.68 to 0.46 for HRTs of three and two days, respectively. The BOD₅ removal efficiencies in thermophilic UASB reactor ranged from 77 to 86% and 74 to 78% for HRTs of three and two days, respectively. The BOD₅ effluent concentrations ranged from 210 to 287 mg/L and 287 to 314 mg/L for HRTs of three and two days, respectively. The BOD₅/COD ratios in thermophilic UASB reactor were 0.57 and 0.51 for HRTs of three and two days, respectively.

The average BOD₅ removal efficiencies at steady state conditions were 87% and 80% for mesophilic and thermophilic UASB reactors at HRT of three days, respectively and at HRT of two days were 82% and 76% for mesophilic and thermophilic UASB reactors, respectively. The average effluent BOD₅ concentration of 175 mg/L was reached in mesophilic UASB reactor at steady state while the average effluent BOD₅ concentration of 264 mg/L was achieved in thermophilic UASB reactor at HRT of three days. At HRT of two days, the average effluent BOD₅ concentrations of

219 mg/L and 299 mg/L were reached in mesophilic and thermophilic UASB reactors respectively at steady state condition.

4.2.2 COD and BOD₅ in Mesophilic and Thermophilic HUASB Reactors

The HUASB reactors were put in operation 62 days after the UASB reactors. For the first 12 days, the HUASB reactors were fed with low strength wastewater at HRT of three days. The reactors were fed with influent COD concentration of 503-519 mg/L with OLR of 0.16-0.18 g COD/L-day. The COD concentration in HUASB reactors is shown in Figure 4.20 and the HUASB reactors performance in this study is shown in Figure 4.21. The COD removal efficiency ranged from 84 to 92% and 46 to 69% for mesophilic and thermophilic HUASB reactors, respectively. The average COD removal efficiencies at steady state conditions were 88% and 66% for mesophilic and thermophilic HUASB reactors, respectively. Statistical analysis (ANOVA; $P < 0.05$) showed that there was significant difference in the COD removal of the mesophilic and thermophilic HUASB reactors at HRT of three days.

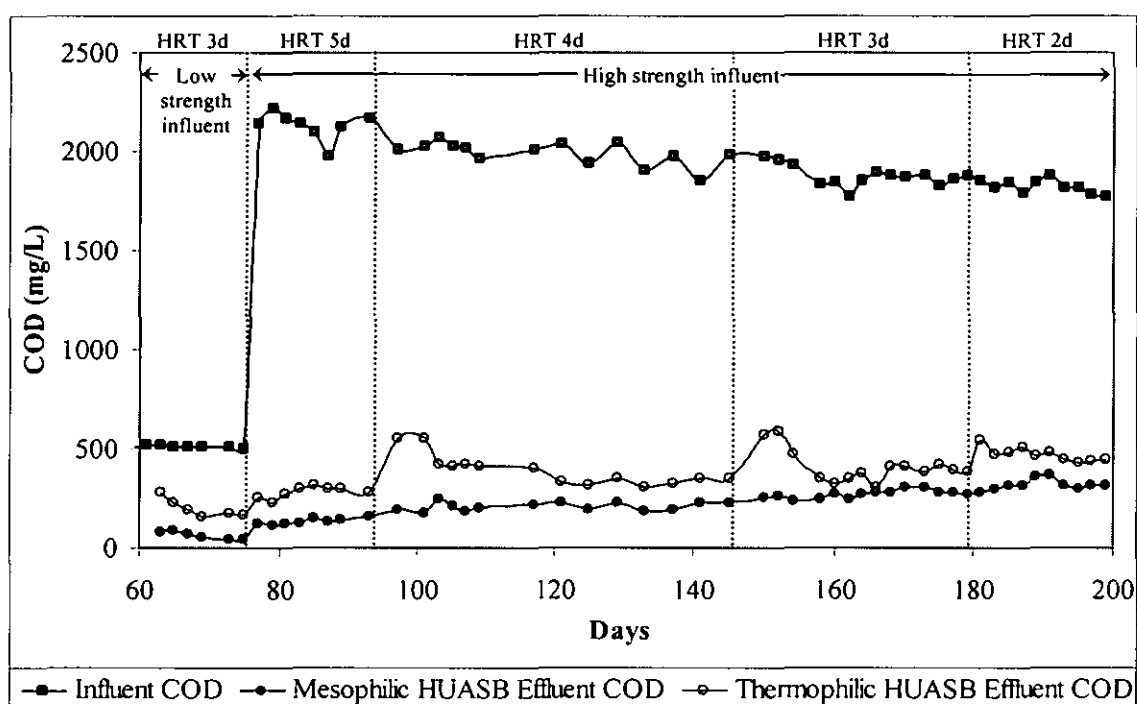


Figure 4.20 Influent and effluent COD concentrations in HUASB reactors

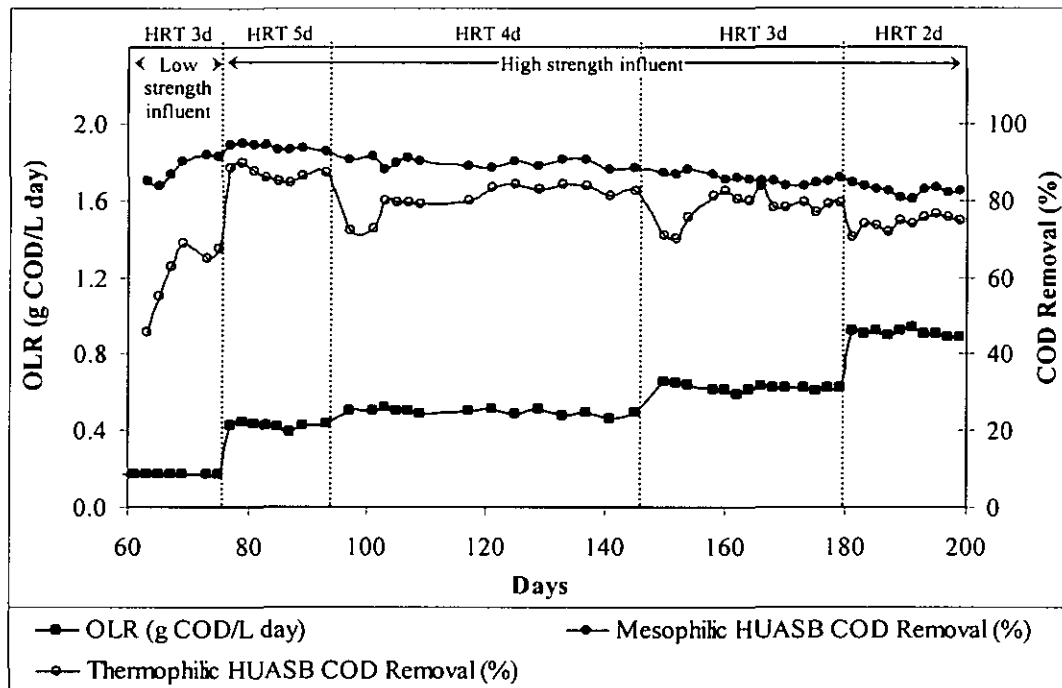


Figure 4.21 OLR and COD removal in HUASB reactors

After 12 days, the reactors were fed with high strength wastewater at HRTs of five, four, three and two days. The HUASB reactors were fed with influent COD concentration of 1170-2217 mg/L with OLR ranged from 0.39 to 0.94 g COD/L-day. From day 76 to day 93, the HUASB reactors were operated at HRT of five days and the average OLR was 0.43 g COD/L-day at which the COD removals ranged from 93 to 95% and 85 to 90% for mesophilic and thermophilic HUASB reactors, respectively. The HUASB reactors were operated with influent COD concentration of 1970-2217 mg/L. The removal efficiency of the mesophilic HUASB increased slightly when the HRT of reactor was changed to two days. However, the efficiency of the thermophilic HUASB reactor increased sharply from 68 to 88% in two days. Furthermore, the effluent COD concentrations increased sharply in both HUASB reactors due to the increase in influent concentration. The mesophilic HUASB reactor reached steady state with average COD removal of 94% while the average COD removal of the thermophilic HUASB reactor was 87%. The average effluent COD concentrations were 133 mg/L and 281 mg/L for mesophilic and thermophilic HUASB reactors, respectively. In addition, the mesophilic and thermophilic HUASB

reactors showed a significantly increase in COD removal (ANOVA; $P < 0.05$) as the HRT was increased from three to five days with the feed of high strength pharmaceutical wastewater. Furthermore, at each HRT, the COD removal was significantly greater in the mesophilic temperature than in the thermophilic temperature (ANOVA; $P < 0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From day 94 to day 145, the HUASB reactors were operated at HRT of four days and the average influent COD concentration of 1989 mg/L. The OLR ranged from 0.46 to 0.52 g COD/L·day. The COD removal efficiency of the mesophilic HUASB dropped slightly to reach steady state conditions within three day, whereas the COD removal dropped sharply from 85 to 72% in thermophilic HUASB reactor. The effluent COD concentrations ranged from 177 to 247 mg/L and 304 to 556 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The HUASB reactor reached steady state after nine days and the average COD removal was 82% while in mesophilic HUASB reactor, the average COD removal was 90%. The average effluent COD concentration in mesophilic HUASB reactor was 208 mg/L while in thermophilic UASB reactor was 366 mg/L. The mesophilic HUASB reactor showed a significantly lower COD removal (ANOVA; $P < 0.05$) as the HRT was decreased from five to four days. However, the thermophilic HUASB reactor showed no significant difference in COD removal (ANOVA; $P < 0.05$). Furthermore, the COD removal at mesophilic temperature was significantly higher from that at thermophilic temperature (ANOVA; $P < 0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

From day 146 to day 179, the HUASB reactors were operated at HRT of three days with influent COD concentration of 1773-1977 mg/L. The average OLR increased from 0.50 to 0.62 g COD/L·day. The COD removal decreased rapidly in thermophilic HUASB reactors in four days while in mesophilic HUASB reactor, the COD removal decreased faintly. The COD removal increased slightly after eight days. The result showed that the thermophilic HUASB reactor was more unstable worked with the changing of OLR, unlike the mesophilic reactor that was stable. The effluent COD

ranged from 234 to 304 mg/L and 305 to 591 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The COD removal efficiencies ranged from 84 to 88% and 70 to 84% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent COD concentration and percentage COD removal at steady state were 270 mg/L and 86% for mesophilic HUASB reactor and 382 mg/L and 79% for thermophilic HUASB reactor, respectively. Based on statistical analysis (ANOVA; $P < 0.05$), the COD removal at HRT of three days was significantly decreased if it was compared with COD removal at HRT of four days in mesophilic HUASB reactor. While in thermophilic HUASB reactor, there was no significant difference between the COD removal at HRT of four days with HRT of three days.

From day 180 to day 199, the HUASB reactors were operated at HRT of two days with influent COD concentration of 1770-1877 mg/L. The OLR ranged from 0.89 to 0.94 g COD/L-day. The COD removal efficiency of the thermophilic HUASB dropped roughly in a day from 79 to 71%, after which it increased slightly. It might be due to the organic shock loading that resulted from the increased wastewater flow rate. The average OLR increased from 0.62 to 0.91 g COD/L-day. In mesophilic HUASB reactor; however, the COD removal efficiency decreased only marginally from 86 to 85%. The COD removal efficiencies varied from 80 to 85% and 71 to 76% for mesophilic and thermophilic HUASB reactors, respectively, while the effluent COD concentrations ranged from 285 to 371 mg/L and 432 to 545 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average COD removal efficiencies at steady state conditions were 83% and 74% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent COD concentration in mesophilic UASB reactor was 319 mg/L while in thermophilic HUASB reactor was 473 mg/L. The mesophilic HUASB reactor showed no significant difference in the COD removal (ANOVA; $P < 0.05$) as the HRT was decreased from three to two days while the thermophilic HUASB reactor showed a significantly lower COD removal. Furthermore, the COD removal at mesophilic temperature at HRT of two days was significantly higher from that at thermophilic temperature (ANOVA; $P < 0.05$). The detail of one-way ANOVA analysis is shown in APPENDIX B: Table B.1.

Nandy and Kaul (2001) observed that the decrease in conversion efficiency with reduction in HRT is greater at higher substrate concentration. It indicated that the system became more organically stressed at higher organic loading. Variation in HRT at constant organic substrate loading by varying feed substrate concentration indicates that performance efficiency varies linearly; increasing with increase in HRT. By optimizing the substrate loading rate, the system can be operated at the loading either by increasing influent substrate concentration with high HRT or operating with low HRT and low influent substrate concentration. Nandy and Kaul (2001) showed that HRT between 5.0 and 2.5 days could be identified as critical, depending on feed substrate concentration.

The performances of the HUASB reactors were also evaluated in terms of BOD₅ removal from day 62 after the UASB reactors were operated. For the first 12 days, the reactors were fed with influent BOD₅ of 325-383 mg/L at HRT of three days. The BOD₅ concentration during this study in HUASB reactors is shown in Figure 4.22 and the BOD₅ removal in HUASB reactors during this study is shown in Figure 4.23. The BOD₅ removal efficiency in mesophilic HUASB reactor ranged from 90 to 95% while the BOD₅ removal in thermophilic HUASB reactor ranged from 70 to 80%. The effluent BOD₅ concentrations were from 20 to 36 mg/L and 31 to 39 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average BOD₅ removal efficiency and average effluent BOD₅ concentration in mesophilic HUASB reactor at steady state conditions were 93% and 27 mg/L, respectively, while the average COD removal of 83% and average effluent COD concentration of 83 mg/L were achieved in thermophilic HUASB reactor. The BOD₅/COD ratio in the wastewater ranged from 0.68 to 0.72 during the operation of the HUASB reactors. The average BOD₅ removal and BOD₅/COD ratio in HUASB reactors are shown in Figure 4.24. At HRT of three days, the BOD₅/COD ratio of low strength pharmaceutical wastewater was 0.68. After treatment by the HUASB reactors, BOD₅/COD ratios were 0.45 and 0.37 for mesophilic and thermophilic temperatures, respectively.

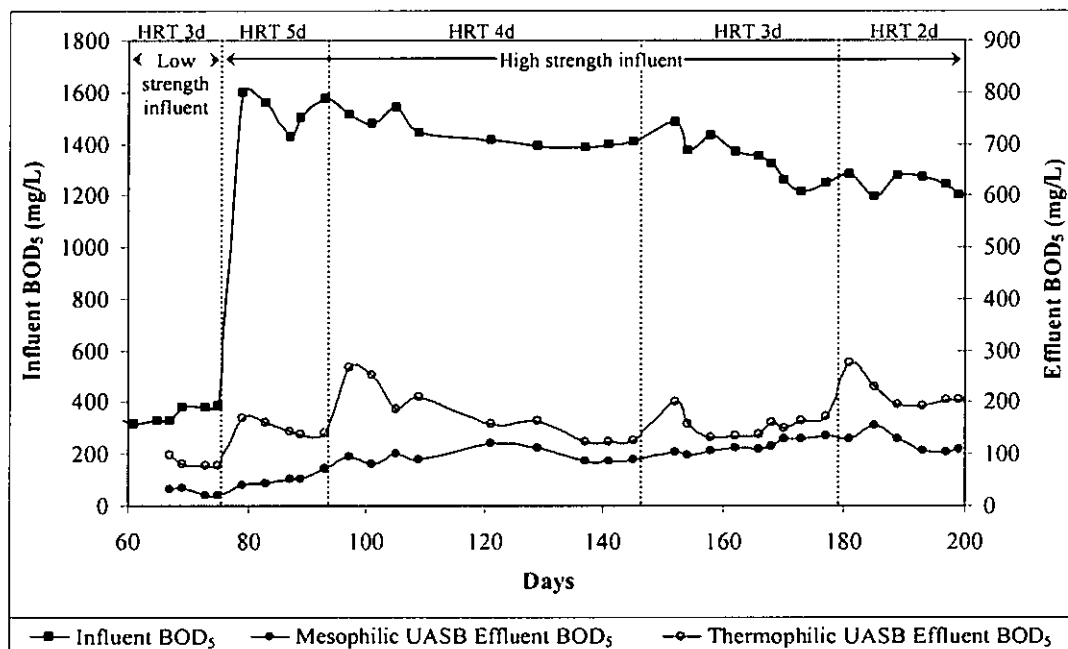


Figure 4.22 Influent and effluent BOD_5 concentrations in HUASB reactors

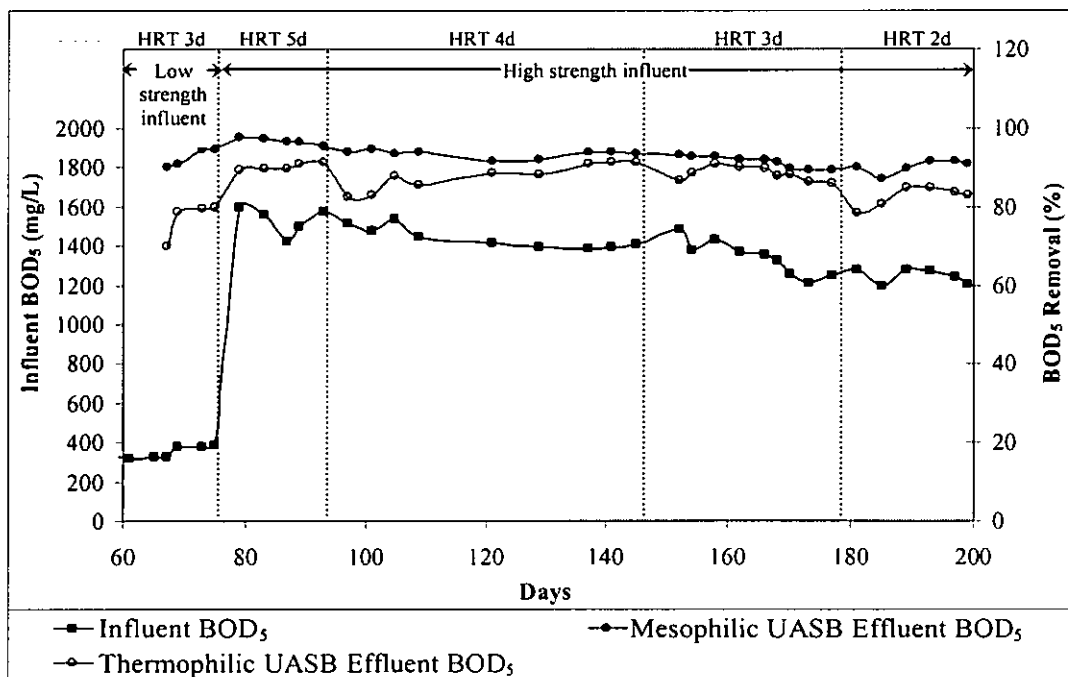


Figure 4.23 Influent BOD_5 concentration and BOD_5 removal in HUASB reactors

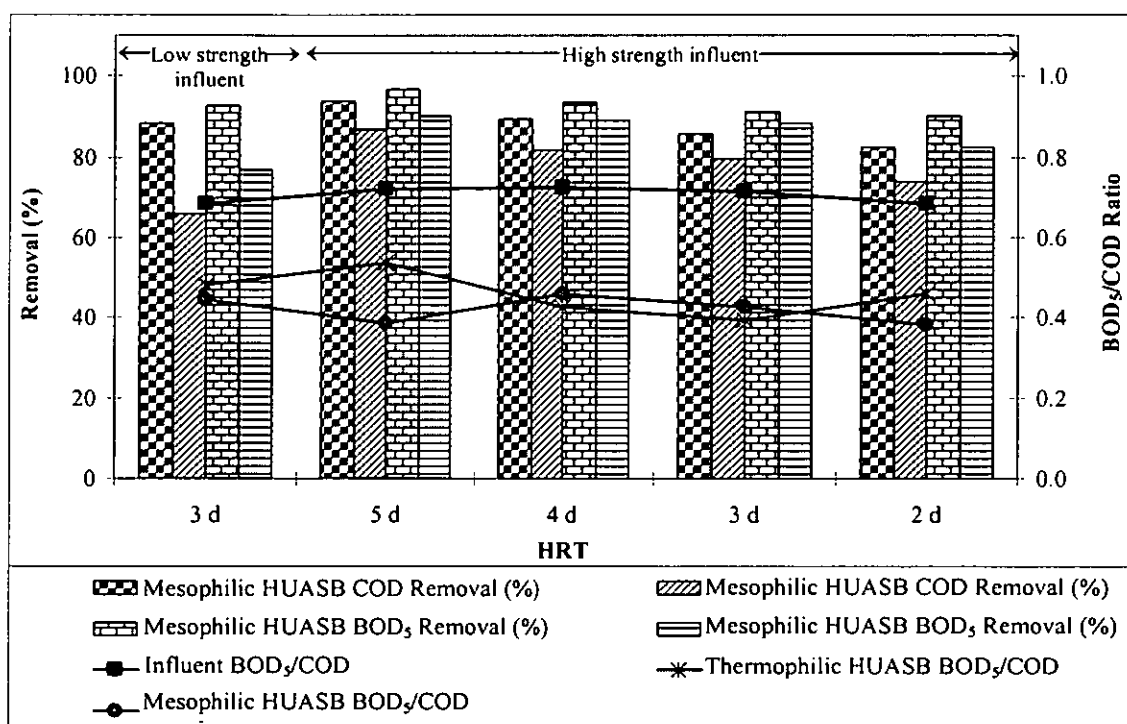


Figure 4.24 Average BOD₅ and COD removals and BOD₅/COD ratio in HUASB reactors at steady state condition

After 13 days, the HRT was increased from three to five days to avoid shock organic loading due to the increased pharmaceutical wastewater COD and BOD₅ concentrations. The average effluent BOD₅ concentration increased from 501 to 1938 mg/L. The BOD₅ concentration ranged from 1427 to 1600 mg/L. The effluent BOD₅ concentrations were from 40 to 71 mg/L and 138 to 171 mg/L for mesophilic and thermophilic HUASB reactors, respectively, while the BOD₅ removal efficiencies ranged from 95 to 97% and 89 to 91% for mesophilic and thermophilic HUASB reactors, respectively. At steady state conditions, the average effluent BOD₅ concentration and average BOD₅ removal were 51 mg/L and 97% in mesophilic HUASB reactor, respectively, whereas in thermophilic HUASB reactor were 151 mg/L and 90%, respectively. The BOD₅/COD ratio of pharmaceutical wastewater at HRT of five days was 0.72 while the BOD₅/COD ratio of the mesophilic and thermophilic HUASB reactors were 0.39 and 0.54, respectively.

From day 94 to day 145, the HUASB reactors were operated at HRT of four days with influent BOD₅ concentration of 1388-1540 mg/L. The BOD₅ removal efficiencies varied from 92 to 95% and 82 to 91% for mesophilic and thermophilic HUASB reactors, respectively, while the effluent BOD₅ concentrations ranged from 81 to 120 mg/L and 123 to 267 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average BOD₅ removal efficiencies at steady state conditions were 93% and 89% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent BOD₅ concentration in mesophilic HUASB reactor was 96 mg/L while in thermophilic HUASB reactor was 156 mg/L. The BOD₅/COD ratio of pharmaceutical wastewater at HRT of four days was 0.72 while the BOD₅/COD ratios of the mesophilic and thermophilic HUASB reactors were 0.46 and 0.43, respectively.

From day 146 to day 179, the HUASB reactors were operated at HRT of three days. The influent BOD₅ ranged from 1212 to 1483 mg/L and effluent BOD₅ ranged from 97 to 134 mg/L and 132 to 200 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The BOD₅ removal efficiencies ranged from 89 to 93% and 86 to 91% for mesophilic and thermophilic HUASB reactors, respectively. The average effluent BOD₅ concentrations and BOD₅ removals at steady state were 115 mg/L and 91% for mesophilic HUASB reactor and 150 mg/L and 88% for thermophilic HUASB reactor, respectively. The BOD₅/COD ratio of influent was 0.71 while the BOD₅/COD ratios of the mesophilic and thermophilic HUASB reactors were 0.43 and 0.39, respectively.

For the last 20 days, the HUASB reactors were operated at HRT of two days with influent BOD₅ of 1198-1280 mg/L. The BOD₅ removal efficiencies in mesophilic and thermophilic HUASB reactors at HRT of two days varied from 87 to 92% and 83 to 84%, respectively, while the effluent BOD₅ concentrations ranged from 102 to 156 mg/L and 194 to 276 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The BOD₅/COD ratio in mesophilic HUASB reactor decreased from 0.68 to 0.38 while in thermophilic HUASB reactor decreased from 0.68 to 0.46. The average BOD₅ removal efficiencies at steady state conditions were 90% and 83%

for mesophilic and thermophilic HUASB reactors at HRT of two days, respectively. The average effluent BOD₅ concentration of 122 mg/L was reached in mesophilic HUASB reactor at steady state while the average effluent BOD₅ concentration of 218 mg/L was achieved in thermophilic HUASB reactor.

4.2.3 Summary of UASB and HUASB Reactors Performance

In Phase II study, the UASB and HUASB reactors were fed with low strength and high strength influent at HRTs of five, four, three and two days under mesophilic ($35\pm 2^{\circ}\text{C}$) and thermophilic ($55\pm 2^{\circ}\text{C}$) conditions. The performance of each reactor was evaluated in terms of COD and BOD₅ removals. Table 4.1 and Table 4.2 show the average COD and BOD₅ concentrations obtained from the UASB and HUASB reactors at steady state conditions. The objective of this study was to evaluate the performance of mesophilic and thermophilic UASB and HUASB reactors in treating non-penicillin pharmaceutical wastewater. The reactors were seeded with sludge from an aerobic domestic sewage treatment plant. The results show the HUASB reactors to be significantly more efficient in COD removal than the UASB reactors. The pharmaceutical wastewater was very fluctuative in COD and BOD₅ concentrations. The reactors were fed with low strength influent (COD 458-526 mg/L) and high strength influent (COD 1770-2217 mg/L). The reactors showed higher COD removal in treating high strength wastewater.

This study was also to evaluate the effect of HRT and temperature on the performance of UASB and HUASB reactors. The reactors were operated under mesophilic ($35\pm 2^{\circ}\text{C}$) and thermophilic ($55\pm 2^{\circ}\text{C}$) temperatures and HRTs of five, four, three and two days. The results show that the reactor performance was significantly affected by type of reactors, HRT and temperature. Both mesophilic UASB and HUASB reactors showed higher COD and BOD₅ removals in treating pharmaceutical wastewater.

Table 4.1 Average influent and effluent COD concentrations, OLR and COD removal in UASB and HUASB reactors

HRT (days)	Influent COD (mg/L)	OLR (g COD/L·d)	Mesophilic UASB		Thermophilic UASB	
			Eff. COD (mg/L)	COD Rem. (%)	Eff. COD (mg/L)	COD Rem. (%)
Low strength influent						
5	487	0.10	60	88	95	80
3	505	0.17	65	87	83	84
High strength influent						
5	2127	0.43	158	93	213	90
4	1989	0.50	262	87	329	83
3	1875	0.62	369	80	464	75
2	1820	0.91	478	74	582	68

HRT (days)	Influent COD (mg/L)	OLR (g COD/L·d)	Mesophilic HUASB		Thermophilic HUASB	
			Eff. COD (mg/L)	COD Rem. (%)	Eff. COD (mg/L)	COD Rem. (%)
Low strength influent						
3	505	0.17	61	88	172	66
High strength influent						
5	2127	0.43	133	94	281	87
4	1989	0.50	208	90	366	82
3	1875	0.62	270	86	382	79
2	1820	0.91	319	83	473	74

Table 4.2 Average influent and effluent BOD₅ concentrations and BOD₅ removal in UASB and HUASB reactors

HRT (days)	Influent BOD ₅ (mg/L)	Mesophilic UASB		Thermophilic UASB	
		Eff. BOD ₅ (mg/L)	BOD ₅ Rem. (%)	Eff. BOD ₅ (mg/L)	BOD ₅ Rem. (%)
Low strength influent					
5	305	27	91	35	88
3	345	28	92	34	90
High strength influent					
5	1532	67	96	134	91
4	1441	124	92	197	86
3	1339	175	87	264	80
2	1245	219	82	299	76

HRT (days)	Influent BOD ₅ (mg/L)	Mesophilic HUASB		Thermophilic HUASB	
		Eff. BOD ₅ (mg/L)	BOD ₅ Rem. (%)	Eff. BOD ₅ (mg/L)	BOD ₅ Rem. (%)
Low strength influent					
3	345	27	93	83	77
High strength influent					
5	1532	51	97	151	90
4	1441	96	93	156	89
3	1339	115	91	150	88
2	1245	122	90	218	83

The highest average COD and BOD₅ removals were achieved by the mesophilic HUASB reactor treating high strength pharmaceutical wastewater at HRT of five days (average OLR 0.43 g COD/L·day); average COD removal was 90%, average effluent COD was 133 mg/L, average BOD₅ removal was 97% and average effluent BOD₅ was 51 mg/L. The COD and BOD₅ removals decreased when the HRT was decreased. The lowest average COD and BOD₅ removals were achieved by the thermophilic UASB reactor at HRT of two days. The average COD and BOD₅ removals were 68% and 76%, respectively, whereas the average COD and BOD₅ concentrations were 582 mg/L and 299 mg/L, respectively.

From the two-way ANOVA result, it found that there was a significant effect of reactor configuration, HRT and temperature, so it implied that the mean of COD removal varied between HRTs of five, four, three and two days and temperature of mesophilic and thermophilic. In addition, there was statistical indication of interaction between HRT and type of reactor, thus the effect of HRT on the COD removal varied significantly with the variation of reactor. The COD removal differed due to the effect between HRT with temperature and reactor with temperature. The two-way ANOVA result showed the COD removal varied with the effect of three variable operation conditions. The detail of two-way ANOVA analysis is shown in APPENDIX B: Table B.2.

4.2.4 Nutrients in Mesophilic and Thermophilic UASB Reactors

Figure 4.25 to Figure 4.32 show the influent and effluent nutrient concentrations (NH₃-N, NO₃-N, TKN and TP) in UASB reactors. In the first 13 days, the UASB reactors were operated at HRT of five days and the influent NH₃-N and NO₃-N concentrations ranged from 3.0 to 3.7 mg/L and 0.6 to 0.9 mg/L, respectively. The effluent NH₃-N increased in both UASB reactors during this study, whereas the NO₃-N was not significantly difference between the influent and effluent of the UASB reactors. The effluent NH₃-N and NO₃-N concentrations in mesophilic UASB reactor ranged from 11.5 to 13.0 mg/L and 0.4 to 0.7 mg/L, respectively, while in thermophilic reactor they ranged from 18.5 to 13.0 mg/L and 0.1 to 0.4 mg/L, respectively.

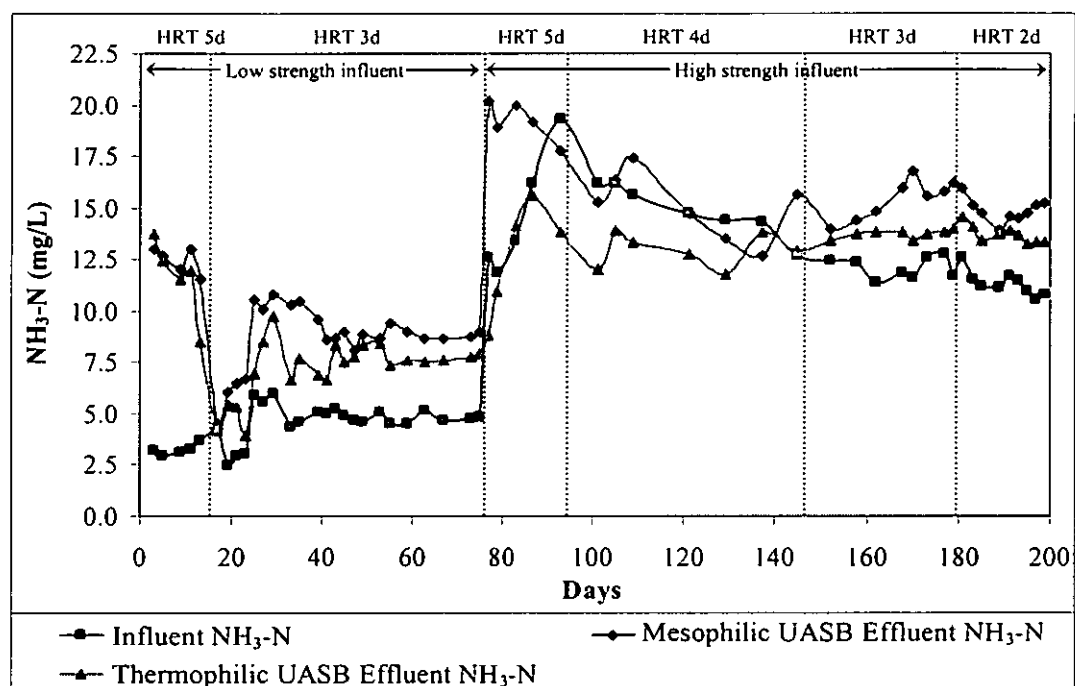


Figure 4.25 Influent and effluent $\text{NH}_3\text{-N}$ concentrations in UASB reactors

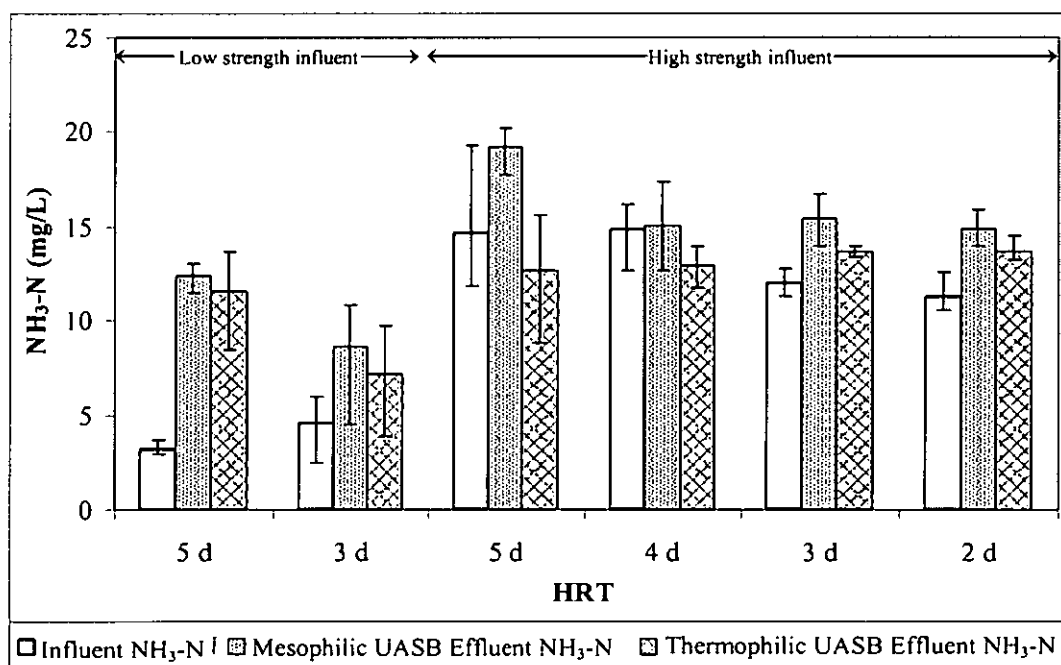


Figure 4.26 Average influent and effluent $\text{NH}_3\text{-N}$ concentrations at each variation of HRT in UASB reactors

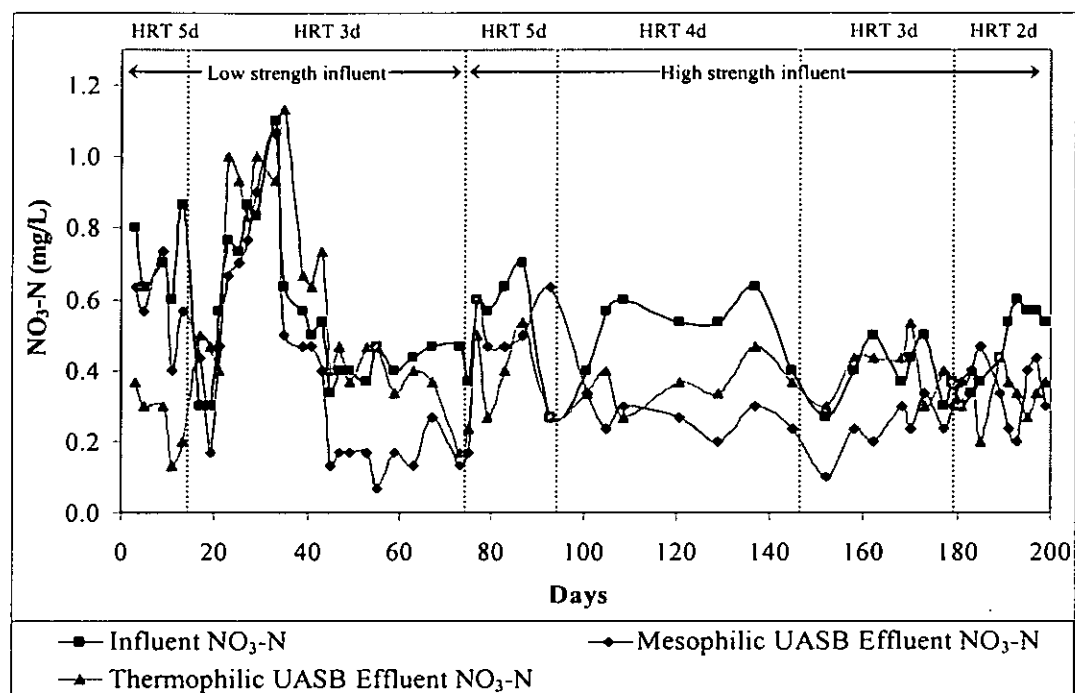


Figure 4.27 Influent and effluent $\text{NO}_3\text{-N}$ concentrations in UASB reactors

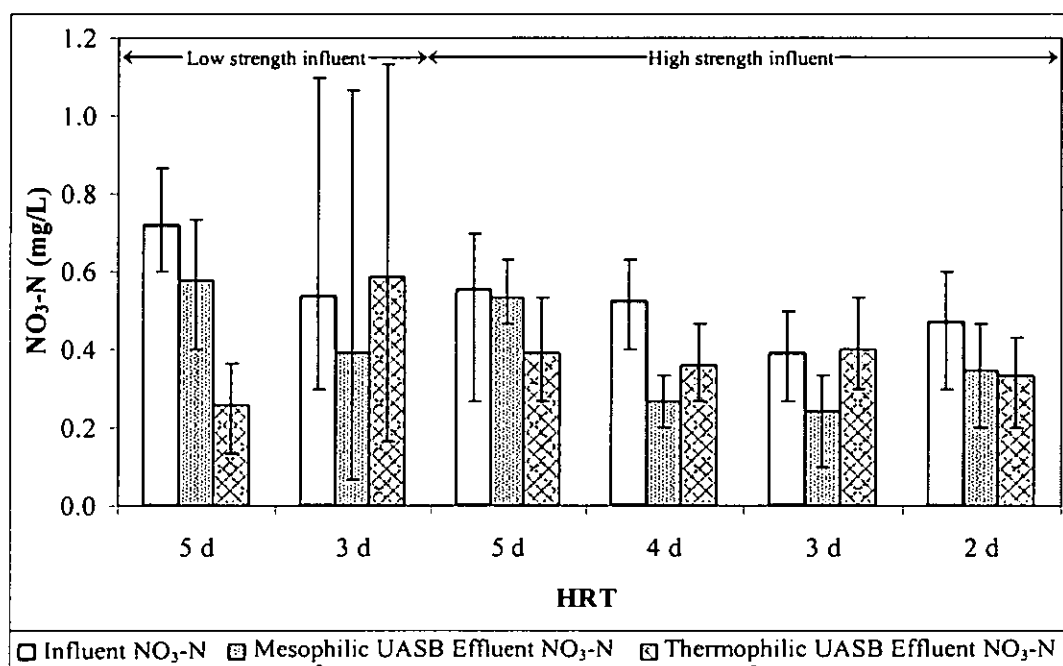


Figure 4.28 Average influent and effluent $\text{NO}_3\text{-N}$ concentrations at each variation of HRT in UASB reactors

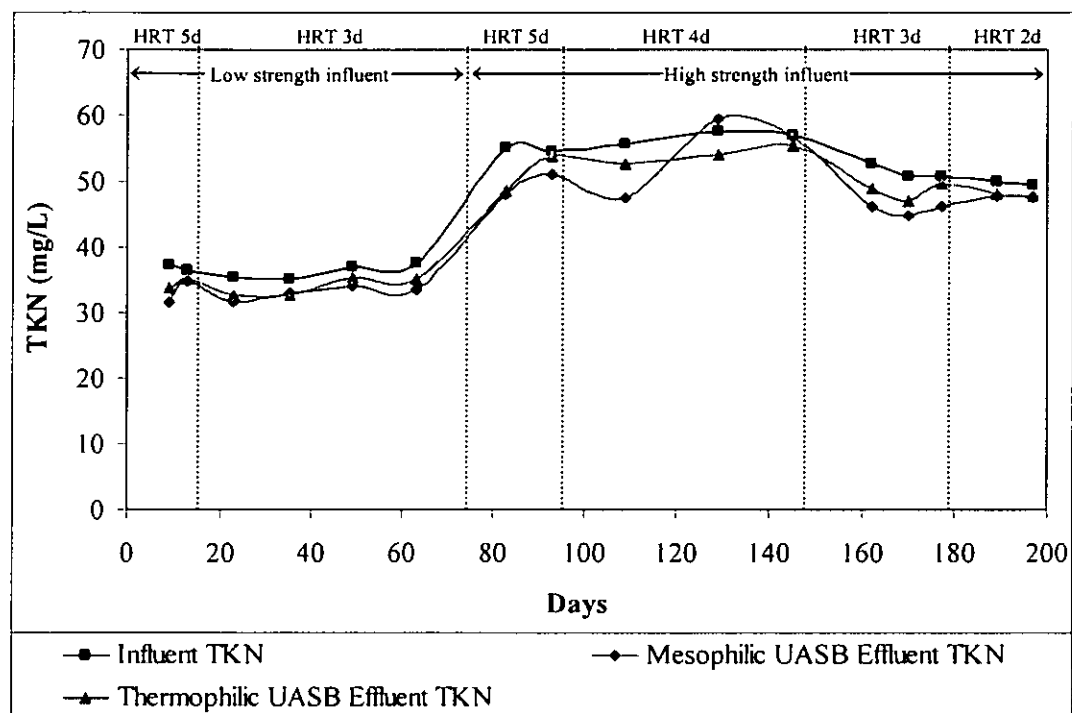


Figure 4.29 Influent and effluent TKN concentrations in UASB reactors

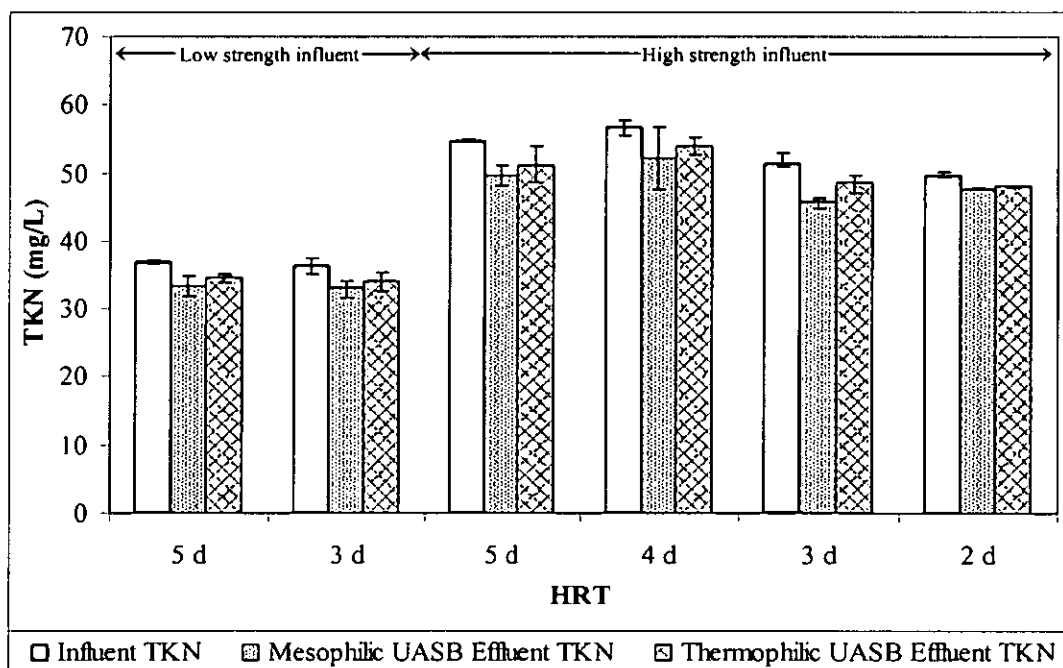


Figure 4.30 Average influent and effluent TKN concentrations at each variation of HRT in UASB reactors

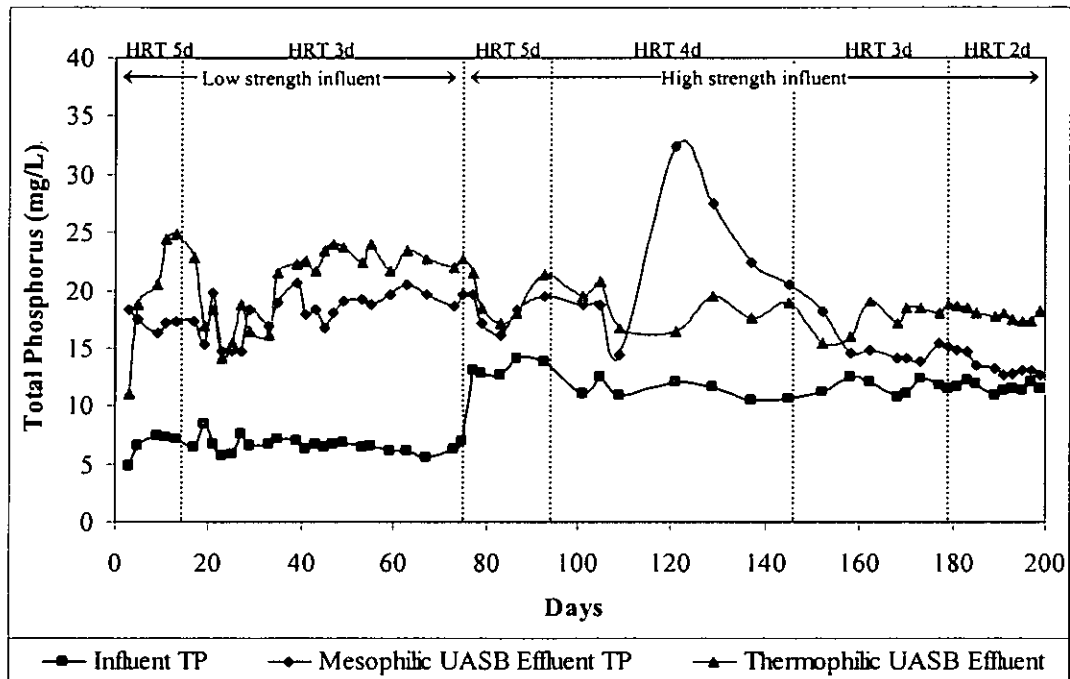


Figure 4.31 Influent and effluent TP concentrations in UASB reactors

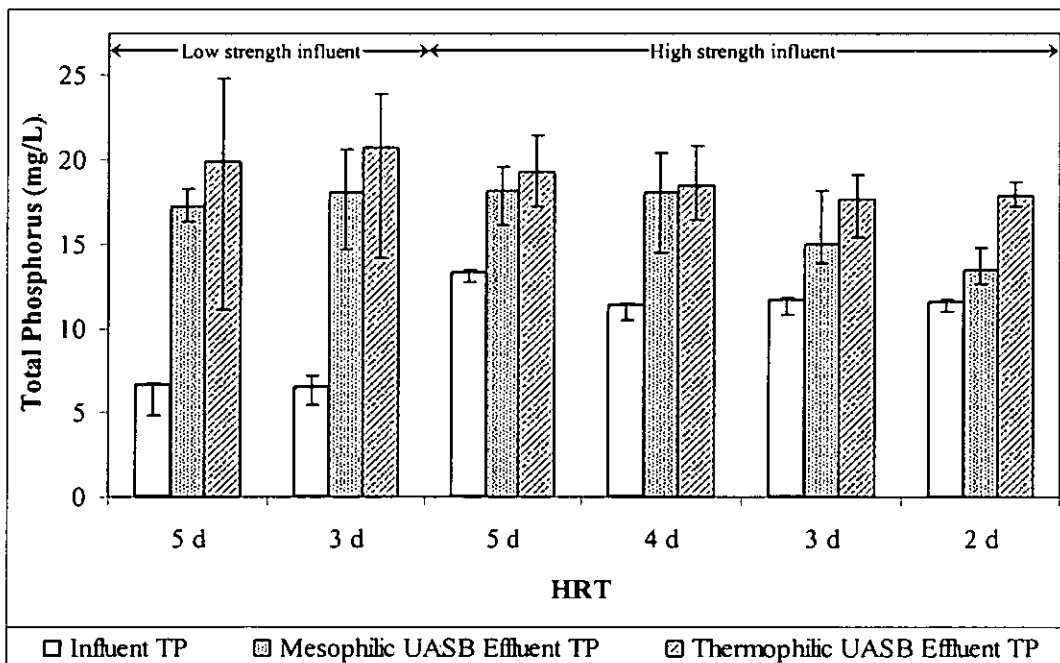


Figure 4.32 Average TP concentration at each variation of HRT in UASB reactors

In low strength pharmaceutical wastewater (COD 458-499 mg/L), the average TKN and TP concentrations of pharmaceutical wastewater were 36.9 mg/L and 6.6 mg/L, respectively at HRT of five days. The COD:TKN:TP ratio was 67:5:1. The average effluent TKN concentrations were 33.3 mg/L and 34.6 mg/L for mesophilic and thermophilic UASB reactors, respectively. Moreover, the average effluent TP concentrations were 17.3 mg/L and 19.9 mg/L. The average TKN and TP concentrations are shown in Figure 4.30 and Figure 4.32, respectively. The COD:TKN:TP ratios decreased from 67:5:1 to 3:2:1 and 4:2:1 for mesophilic and thermophilic UASB reactors, respectively.

At HRT of three days, the average effluent $\text{NH}_3\text{-N}$ of the mesophilic UASB reactor was higher than the thermophilic UASB reactor whereas the average effluent $\text{NO}_3\text{-N}$ of the mesophilic UASB reactor was lower than the thermophilic UASB reactor. The average $\text{NH}_3\text{-N}$ concentrations increased from 4.6 to 8.7 mg/L and 4.6 to 7.2 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average $\text{NO}_3\text{-N}$ concentrations were relatively constant from 0.4 to 0.5 mg/L and 0.5 to 0.6 mg/L for mesophilic and thermophilic UASB reactors, respectively. The influent and effluent $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in UASB reactors during this study are shown in Figure 4.25 to Figure 4.28, respectively. From day 14 to day 75, the UASB reactors were fed by low strength pharmaceutical wastewater (COD 483-526 mg/L) and TP concentrations of pharmaceutical wastewater varied from 5.5 to 8.5 mg/L. The effluent TP concentrations in mesophilic and thermophilic UASB reactors ranged from 14.7 to 20.6 mg/L and 14.1 to 23.9 mg/L, respectively. The influent and effluent TP concentrations in UASB reactors during this study are shown in Figure 4.31. The average TKN concentration of pharmaceutical wastewater was 36.3 mg/L, while the average effluent TKN concentrations were 33.1 mg/L and 34 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD:TKN:TP ratios decreased from 79:6:1 to 3:2:1 and 5:2:1 for mesophilic and thermophilic UASB reactors, respectively.

From day 76, the UASB reactors were fed with high strength wastewater (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. At HRT of

five days, the average influent $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations were 14.7 mg/L and 0.6 mg/L, respectively. The $\text{NH}_3\text{-N}$ concentration increased in mesophilic UASB reactor (from 14.7 to 19.2 mg/L) whereas in thermophilic UASB reactor, it decreased (from 14.7 to 12.7 mg/L). The $\text{NO}_3\text{-N}$ concentrations slightly decreased in both UASB reactors. The average effluent $\text{NO}_3\text{-N}$ concentrations in mesophilic and thermophilic UASB reactor were 0.5 mg/L and 0.4 mg/L, respectively. In high strength pharmaceutical wastewater (COD 1970-2217 mg/L) when the UASB reactors were operated at HRT of five days, the average TKN and TP concentrations of pharmaceutical wastewater were 54.8 mg/L and 13.3 mg/L, respectively. The COD:TKN:TP ratio of pharmaceutical wastewater was 163:4:1. The average effluent TKN concentrations were 49.7 mg/L and 51.2 mg/L for mesophilic and thermophilic UASB reactors, respectively. Moreover, the average effluent TP concentrations were 18.2 mg/L and 19.3 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD:TKN:TP ratios decreased from 163:4:1 to 10:3:1 and 13:2:1 for mesophilic and thermophilic UASB reactors, respectively.

From day 94 to day 145, the UASB reactors were operated at HRT of four days. The average effluent $\text{NH}_3\text{-N}$ of the mesophilic UASB reactor was higher than that of the thermophilic UASB reactor whereas the average effluent $\text{NO}_3\text{-N}$ of the mesophilic UASB reactor was lower than that of the thermophilic reactor. The average $\text{NH}_3\text{-N}$ concentrations increased from 14.9 to 15.1 mg/L and 14.9 to 13.0 mg/L for mesophilic and thermophilic UASB reactors, respectively. The average $\text{NO}_3\text{-N}$ concentrations were relatively constant from 0.3 to 0.4 mg/L and 0.3 to 0.5 mg/L for mesophilic and thermophilic UASB reactors, respectively. At HRT of four days, the UASB reactors were fed by high strength pharmaceutical wastewater (COD 1853-2073 mg/L) and average TP concentrations of pharmaceutical wastewater was 11.3 mg/L. The average effluent TP concentration in mesophilic and thermophilic UASB reactors were 18.1 mg/L and 18.5 mg/L, respectively. The average TKN concentration of pharmaceutical wastewater was 56.7 mg/L, while the average effluent TKN concentrations were 52.2 mg/L and 56.7 mg/L for mesophilic and thermophilic UASB reactors, respectively. The COD:TKN:TP ratios decreased

from 180:5:1 to 19:3:1 and 18:3:1 for mesophilic and thermophilic UASB reactors, respectively.

On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The temperature increased to 60°C. From day 111 to day 118, the mesophilic UASB reactor was operated at ambient temperature ($24\pm 2^\circ\text{C}$) while it was being repaired. The effluent $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations ranged from 12.7 to 14.7 mg/L and 0.2 to 0.3 mg/L, respectively. The effluent $\text{NH}_3\text{-N}$ concentrations were lower than the effluent $\text{NH}_3\text{-N}$ concentrations before the mesophilic UASB reactor failed while the effluent $\text{NO}_3\text{-N}$ concentrations relatively did not change, whereas the effluent TP concentrations sharply increased. The effluent TP concentration ranged from 22.4 to 32.5 mg/L. The results for the reactor breakdown period were not included for data analysis. The TKN concentration increased from 57.7 mg/L (influent) to 59.6 mg/L (effluent). After 30 days, the reactor stabilized with effluent TP of 20.5 mg/L.

From day 146 to day 179, the UASB reactors were operated at HRT of three days, while for the last 20 days, the UASB reactors were operated at HRT of two days. The average influent $\text{NH}_3\text{-N}$ concentrations were 12.1 mg/L and 11.3 mg/L at HRTs of three and two days, respectively. The average effluent $\text{NH}_3\text{-N}$ concentration in mesophilic UASB reactor decreased at the lower HRT, while in thermophilic UASB reactors it remained constant when the HRT was reduced. The average effluent $\text{NH}_3\text{-N}$ concentrations in mesophilic UASB reactor were 15.4 mg/L and 14.9 mg/L at HRTs of three and two days, respectively whereas in thermophilic UASB reactors, it was 13.7 mg/L at both HRTs of three and two days. The average influent $\text{NO}_3\text{-N}$ concentrations were 0.4 mg/L and 0.5 mg/L at HRTs of three and two days, respectively. The average effluent $\text{NO}_3\text{-N}$ concentrations in both UASB reactors were relatively constant when the HRT was reduced. The average effluent $\text{NO}_3\text{-N}$ concentrations in mesophilic UASB reactor were 0.2 mg/L and 0.3 mg/L at HRTs of three and two days, respectively whereas in thermophilic UASB reactors $\text{NO}_3\text{-N}$ concentrations were 0.4 mg/L and 0.3 mg/L at HRTs of three and two days, respectively.

At HRT of three days the pharmaceutical wastewater COD of 1875 mg/L was fed in UASB reactors, whereas COD of 1820 mg/L was fed to the UASB reactor at HRT of two days. The influent COD:TKN:TP ratio was 158:4:1 for both HRTs of three and two days. The average TKN concentrations of pharmaceutical wastewater were 51.5 mg/L and 49.7 mg/L, whereas the average TP concentrations were 11.7 mg/L and 11.6 mg/L for HRTs of three and two days, respectively. The effluent COD:TKN:TP ratio at HRT of three days were lower than the effluent COD:TKN:TP ratio at HRT of two days in both UASB reactors. This is mainly attributed to the increase in effluent COD as the main factor. The effluent COD:TKN:TP ratios were 24:3:1 and 34:4:1 for HRTs of three and two days in mesophilic reactor, respectively whereas in thermophilic reactor, the effluent COD:TKN:TP ratios were 25:3:1 and 34:3:1 for HRTs of three and two days, respectively. In mesophilic UASB reactor, the average effluent TKN concentration increased from 45.7 to 47.7 mg/L when the HRT was decreased from three to two days while in thermophilic UASB reactor, the average effluent TKN concentration slightly decreased from 48.6 to 48.0 mg/L. Moreover, the average effluent TP concentration in mesophilic UASB reactor decreased from 15.0 to 13.4 mg/L while in thermophilic UASB reactor, the average effluent TP concentration slightly increased from 17.7 to 17.9 mg/L when the HRT was decreased from three to two days.

4.2.5 Nutrients in Mesophilic and Thermophilic HUASB Reactors

Figure 4.33 to Figure 4.40 show the influent and effluent nutrient concentrations ($\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$, TKN and TP) in HUASB reactors. The HUASB reactors started operation 62 days after the UASB reactors. For the first 12 days, the HUASB reactors were fed with low strength wastewater at HRT of three days. The influent $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations ranged from 4.6 to 5.1 mg/L and 0.6 to 0.5 mg/L, respectively. The $\text{NH}_3\text{-N}$ concentrations sharply increased in both HUASB reactors during this study whereas the $\text{NO}_3\text{-N}$ concentrations did not significantly change between the influent and effluent of HUASB reactors. The effluent $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in mesophilic HUASB reactor varied from 18.4 to 19.4 mg/L and 0.1 to 0.2 mg/L, respectively, while in thermophilic reactor varied from

13.4 to 14.1 mg/L and 0.2 to 0.3 mg/L, respectively at HRT of three days. The influent and effluent $\text{NH}_3\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in UASB reactors during this study are shown in Figure 4.33 and Figure 4.35, respectively. In low strength pharmaceutical wastewater (COD 503-519 mg/L), the average TKN and TP concentrations of pharmaceutical wastewater were 37.5 mg/L and 6.2 mg/L, respectively. The COD:TKN:TP ratio was 79:6:1. The average effluent TKN concentrations were 31.8 mg/L and 34.1 mg/L for mesophilic and thermophilic HUASB reactors, respectively. Moreover, the average effluent TP concentrations were 26.8 mg/L and 27.2 mg/L for mesophilic and thermophilic HUASB reactors, respectively. The average influent and effluent TKN and TP concentrations in HUASB reactors are shown in Figure 4.38 and Figure 4.40, respectively. The COD:TKN:TP ratios decreased from 67:5:1 to 3:1:1 and 11:1:1 for mesophilic and thermophilic HUASB reactors, respectively.

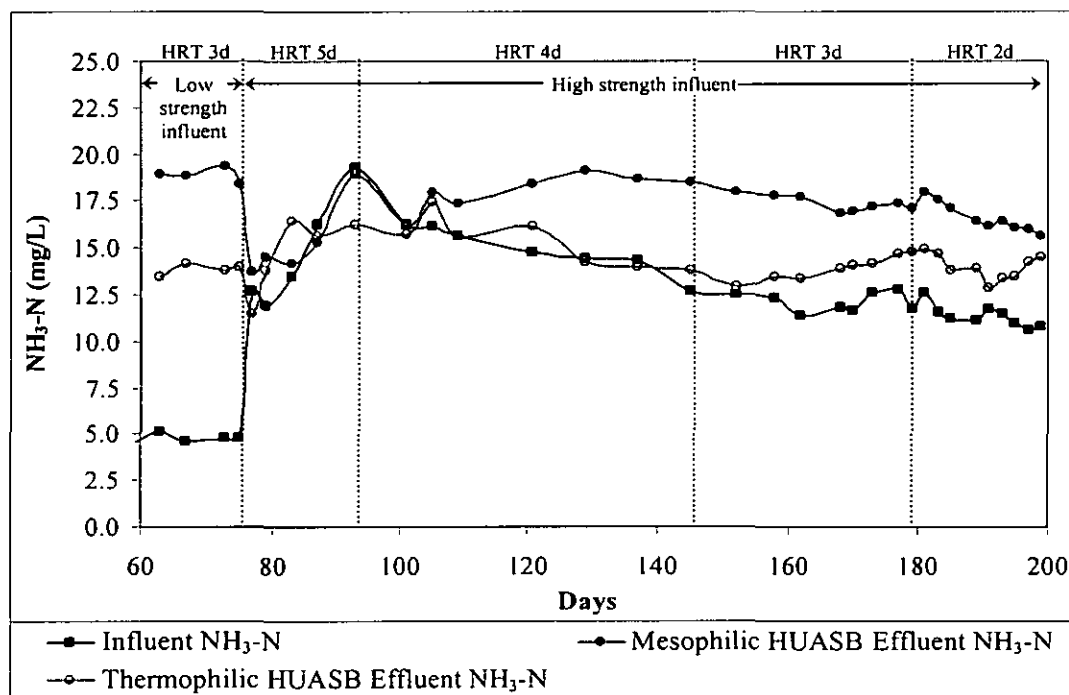


Figure 4.33 Influent and effluent $\text{NH}_3\text{-N}$ concentrations in HUASB reactors

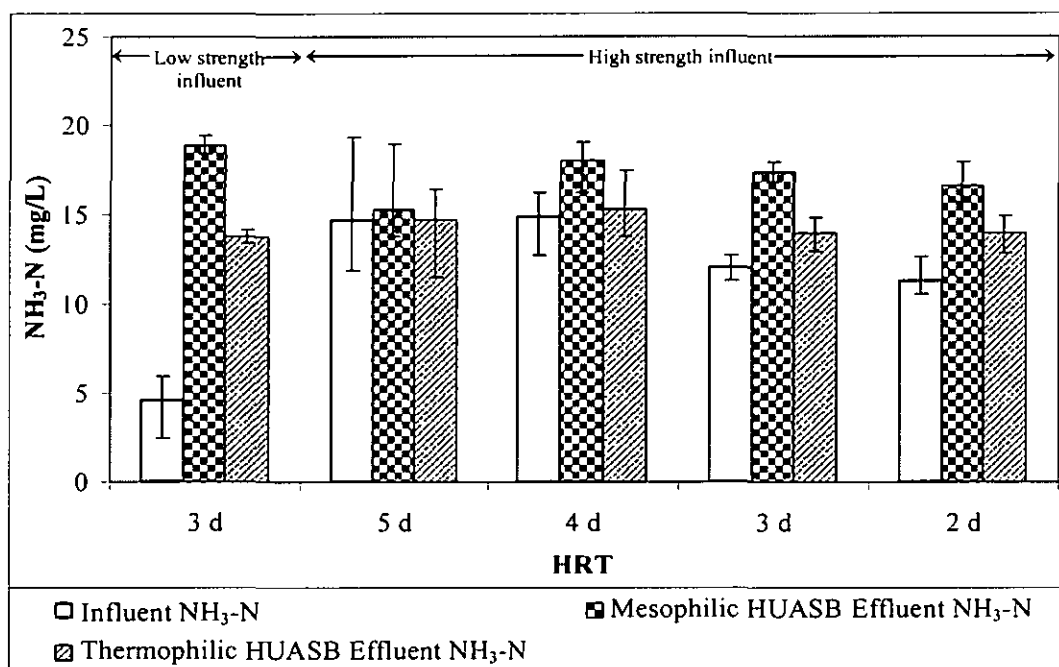


Figure 4.34 Average influent and effluent $\text{NH}_3\text{-N}$ concentrations at each variation of HRT in HUASB reactors

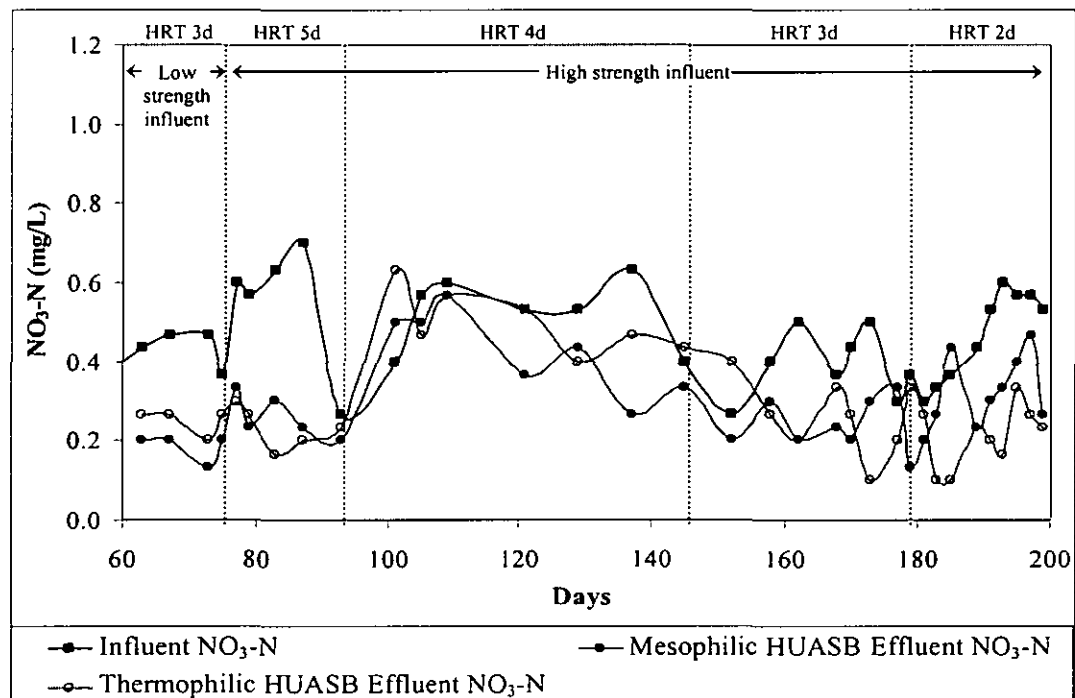


Figure 4.35 Influent and effluent $\text{NO}_3\text{-N}$ concentrations in HUASB reactors

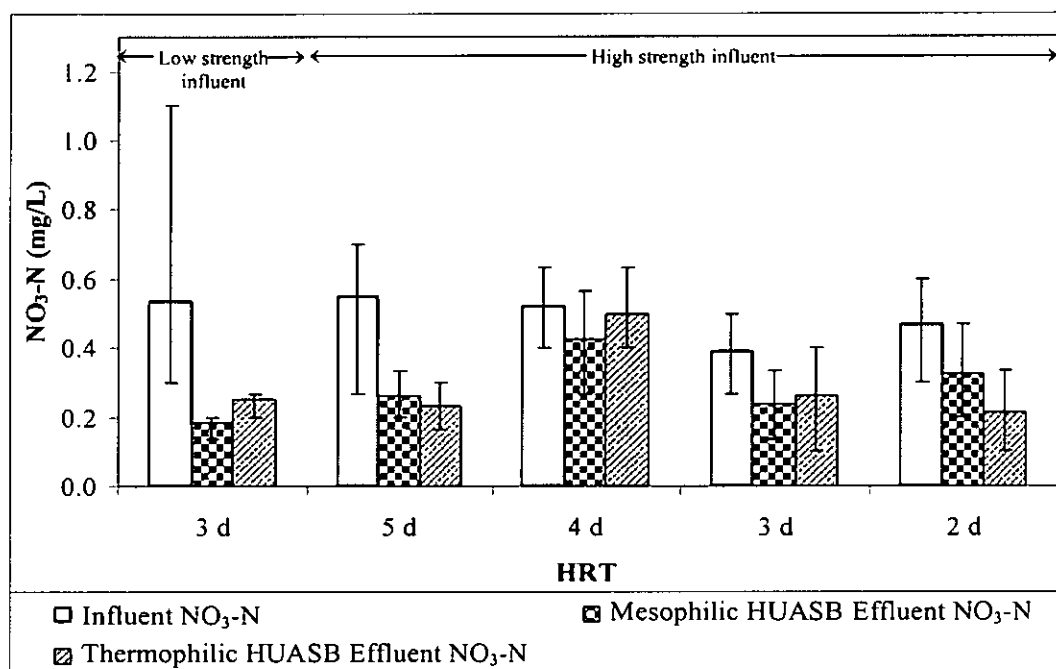


Figure 4.36 Average influent and effluent $\text{NO}_3\text{-N}$ concentrations at each variation of HRT in HUASB reactors

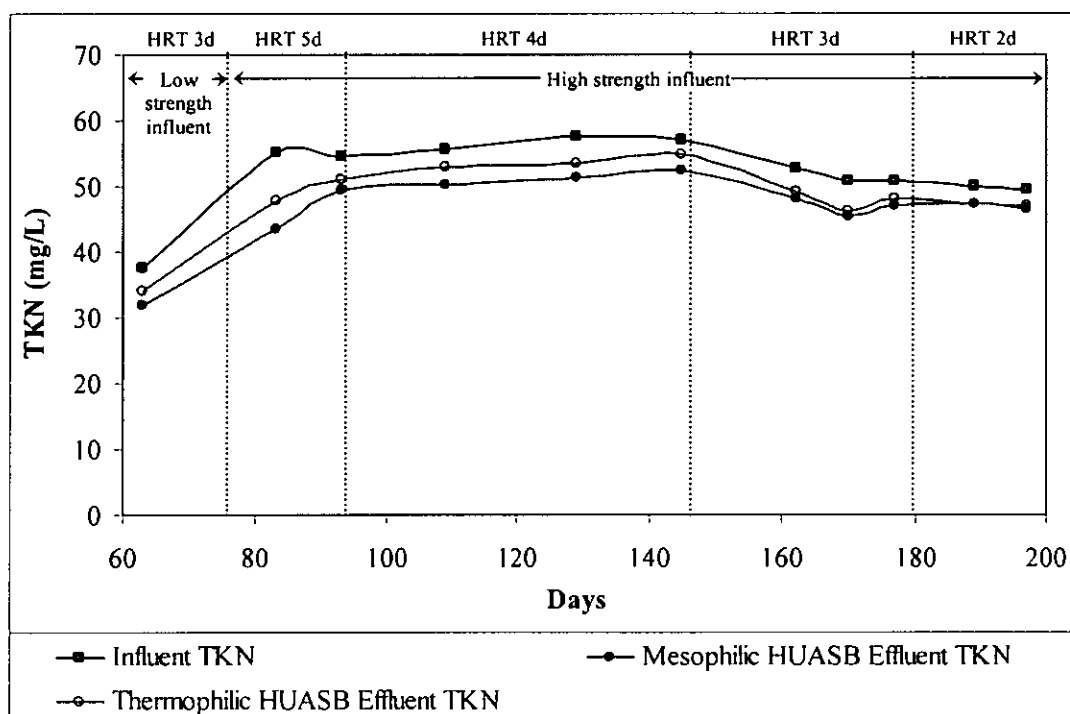


Figure 4.37 Influent and effluent TKN concentrations in HUASB reactors

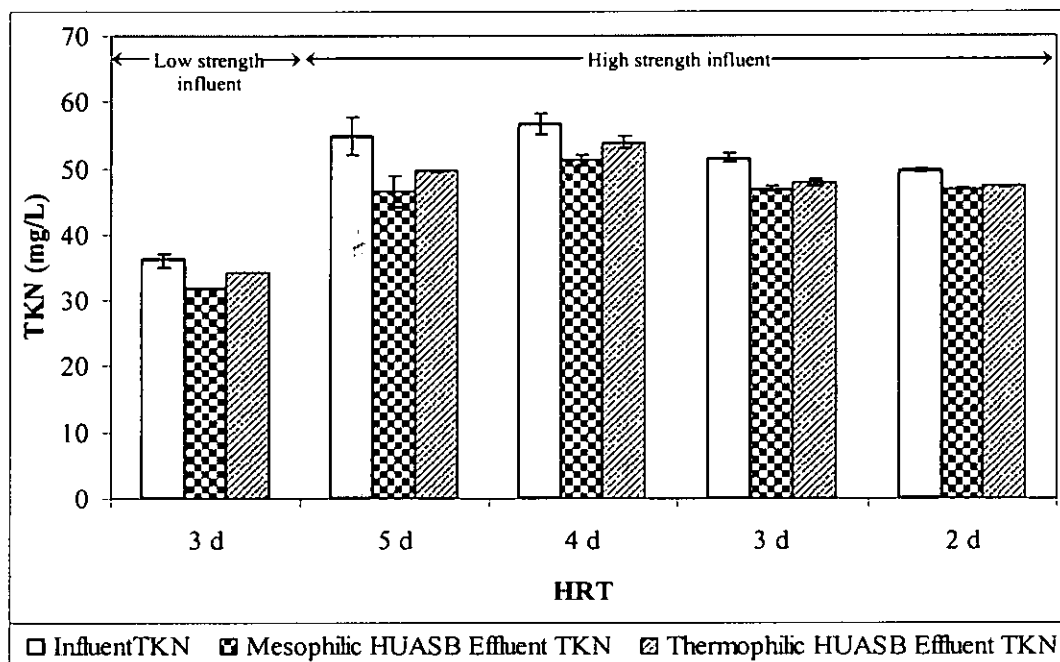


Figure 4.38 Average influent and effluent TKN concentrations at each variation of HRT in HUASB reactors

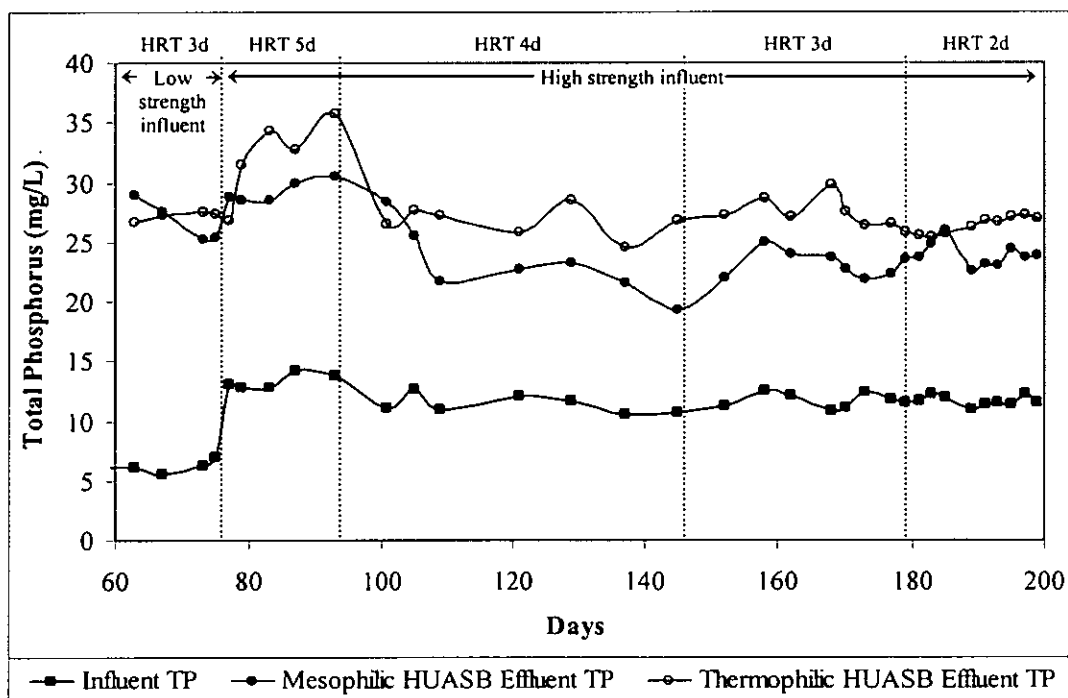


Figure 4.39 Influent and effluent TP concentrations in HUASB reactors

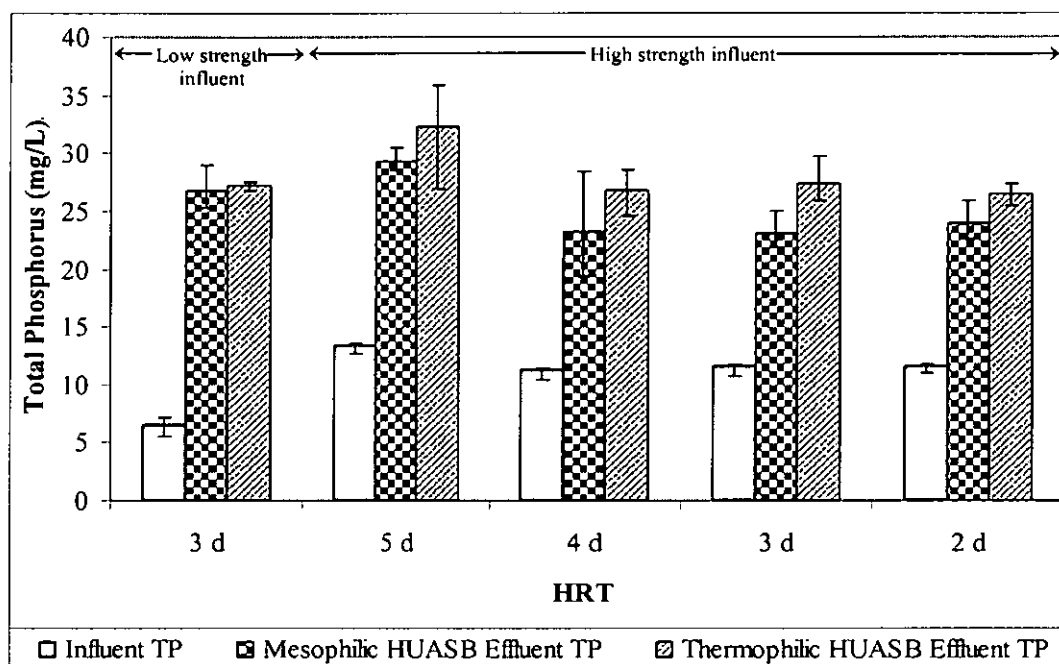


Figure 4.40 Average influent and effluent TP concentrations at each variation of HRT in HUASB reactors

From day 76, high strength wastewater was fed to the HUASB reactors (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. From day 76 to day 93, the HUASB reactors were operated at HRT of five days, while from day 94 to day 145, the HUASB reactors were operated at HRT of four days. The average influent $\text{NH}_3\text{-N}$ concentrations were 14.7 mg/L and 14.9 mg/L at HRT of five and four days, respectively. The average effluent $\text{NH}_3\text{-N}$ concentrations increased in both HUASB reactors when the HRT was reduced. The average effluent $\text{NH}_3\text{-N}$ concentrations in mesophilic HUASB reactor were 15.3 mg/L and 18.0 mg/L at HRTs of five and four days, respectively whereas in thermophilic HUASB reactors, they were 14.7 mg/L and 15.3 mg/L at HRTs of three and two days, respectively. The average influent $\text{NO}_3\text{-N}$ concentrations were 0.6 mg/L and 0.5 mg/L at HRTs of three and two days, respectively. The average effluent $\text{NO}_3\text{-N}$ concentrations in both HUASB reactors were relatively constant when the HRT was reduced. The average effluent $\text{NO}_3\text{-N}$ concentrations in mesophilic HUASB reactor were 0.3 mg/L and 0.4 mg/L at HRTs of three and two days, respectively, whereas in

thermophilic HUASB reactors, they were 0.2 mg/L and 0.5 mg/L at HRTs of three and two days, respectively.

At HRTs of five and four days, the COD concentrations of pharmaceutical wastewater fed to the HUASB reactors were 2127 mg/L and 1989 mg/L, respectively. The influent COD:TKN:TP ratios were 163:4:1 and 180:5:1 for HRTs of five and four days, respectively. The average TKN concentrations of pharmaceutical wastewater were 54.8 mg/L and 56.7 mg/L, whereas the average TP concentrations were 13.3 mg/L and 11.3 mg/L for HRTs of five and four days, respectively. The effluent COD:TKN:TP ratios at HRT of five days were lower than the effluent COD:TKN:TP ratio at HRT of four days in both HUASB reactors. These results are attributed to the increase in effluent COD as the main factor. The effluent COD:TKN:TP ratios were 5:2:1 and 10:4:1 for HRTs of five and four days in mesophilic HUASB reactor, respectively whereas in HUASB thermophilic reactor, the effluent COD:TKN:TP ratios were 8:1:1 and 13:2:1 for HRTs of five and four days, respectively. In mesophilic HUASB reactor, the average effluent TKN concentrations increased from 46.5 to 51.3 mg/L when the HRT was decreased from five to four days while in thermophilic HUASB reactor, the average effluent TKN concentrations increased from 49.5 to 53.8 mg/L. Moreover, the average effluent TP concentrations in mesophilic HUASB reactor decreased from 29.3 to 23.2 mg/L while in thermophilic HUASB reactor, the average effluent TP concentrations decreased from 32.2 to 26.7 mg/L when the HRT was decreased from five to four days.

From day 146 to day 179, the HUASB reactors were operated at HRT of three days and fed by the pharmaceutical wastewater COD of 1875 mg/L, while for the last 20 days, the UASB reactors were operated at HRT of two days and supplied by the pharmaceutical wastewater with COD of 1820 mg/L. At HRT of three days, the average TKN and TP concentrations of pharmaceutical wastewater were 51.5 mg/L and 11.7 mg/L, respectively, whereas at HRT of two days, the average TKN and TP concentrations were 49.7 mg/L and 11.6 mg/L, respectively. In mesophilic HUASB reactor, the average effluent TKN concentrations were about the same

(46.8 mg/L and 46.9 mg/L) when the HRT was decreased from three to two days while in thermophilic HUASB reactor, the average TKN concentration slightly decreased from 47.8 mg/L to 47.2 mg/L. Moreover, the average effluent TP concentration in mesophilic HUASB reactor increased from 23.1 to 23.9 mg/L, while in thermophilic HUASB reactor, the average effluent TP concentration decreased from 27.4 to 26.4 mg/L when the HRT was decreased from three to two days. The influent COD:TKN:TP ratios were 158:4:1 for both HRTs of three and two days. The effluent COD:TKN:TP ratios at HRT of two days were higher than the effluent COD:TKN:TP ratios at HRT of three days in both HUASB reactors. The effluent COD:TKN:TP ratios were 12:2:1 and 15:2:1 for HRTs of three and two days in mesophilic HUASB reactor, respectively whereas in thermophilic HUASB reactor, the effluent COD:TKN:TP ratios were 14:2:1 and 17:2:1 for HRTs of three and two days, respectively.

The average influent $\text{NH}_3\text{-N}$ concentrations were 12.1 mg/L and 11.3 mg/L at HRTs of three and two days, respectively. In mesophilic HUASB reactor, the average effluent $\text{NH}_3\text{-N}$ concentrations decreased and in thermophilic HUASB reactor was constant, when the HRT was reduced. The average effluent $\text{NH}_3\text{-N}$ concentrations in mesophilic HUASB reactor were 17.4 mg/L and 16.6 mg/L at HRTs of three and two days, respectively whereas in thermophilic HUASB reactors were 13.9 mg/L and 14.0 mg/L at HRTs of three and two days, respectively. The average influent $\text{NO}_3\text{-N}$ concentrations were 0.4 mg/L and 0.5 mg/L at HRTs of three and two days, respectively. The average effluent $\text{NO}_3\text{-N}$ concentrations in both HUASB reactors were relatively constant when the HRT was reduced. The average effluent $\text{NO}_3\text{-N}$ concentrations in mesophilic HUASB reactor were 0.2 mg/L and 0.3 mg/L at HRTs of three and two days, respectively whereas in thermophilic HUASB reactors were 0.3 mg/L and 0.2 mg/L at HRTs of three and two days, respectively.

4.2.6 Summary of Nutrient Parameters in UASB and HUASB Reactors

Table 4.1 to Table 4.6 show the average nutrient concentrations ($\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$, TKN and TP) in UASB and HUASB reactors at steady state conditions. The

concentration of $\text{NH}_3\text{-N}$ and total phosphorous increased during this study, whereas the concentration of $\text{NO}_3\text{-N}$ was constant and concentration of TKN slightly reduced. Jenicek et al. (1996) also reported negligible nitrogen removal using a UASB reactor treating biosynthetic pharmaceutical wastewater.

Table 4.3 Average influent and effluent $\text{NH}_3\text{-N}$ concentrations in UASB and HUASB reactors

HRT (days)	Influent NH ₃ -N (mg/L)	Effluent NH ₃ -N (mg/L)				
		Mesophilic UASB	Thermophilic UASB	Mesophilic HUASB	Thermophilic HUASB	
Low strength influent						
5	3.3	12.5	11.6	N/A	N/A	
3	4.6	8.7	7.2	18.9	13.8	
High strength influent						
5	14.7	19.2	12.7	15.3	14.7	
4	14.9	15.1	13.0	18.0	15.3	
3	12.1	15.4	13.7	17.4	13.9	
2	11.3	14.9	13.7	16.6	14.0	

Table 4.4 Average influent and effluent $\text{NO}_3\text{-N}$ concentrations in UASB and HUASB reactors

HRT (days)	Influent NO ₃ -N (mg/L)	Effluent NO ₃ -N (mg/L)				
		Mesophilic UASB	Thermophilic UASB	Mesophilic HUASB	Thermophilic HUASB	
Low strength influent						
5	0.7	0.6	0.3	N/A	N/A	
3	0.5	0.4	0.6	0.2	0.3	
High strength influent						
5	0.6	0.5	0.4	0.3	0.2	
4	0.5	0.3	0.4	0.4	0.5	
3	0.4	0.2	0.4	0.2	0.3	
2	0.5	0.3	0.3	0.3	0.2	

Table 4.5 Average influent and effluent TKN concentrations in UASB and HUASB reactors

HRT (days)	Influent TKN (mg/L)	Effluent TKN (mg/L)			
		Mesophilic UASB	Thermophilic UASB	Mesophilic HUASB	Thermophilic HUASB
Low strength influent					
5	36.9	33.3	34.6	N/A	N/A
3	36.3	33.1	34.0	31.8	34.1
High strength influent					
5	54.8	49.7	51.2	46.5	49.5
4	56.7	52.2	54.0	51.3	53.8
3	51.5	45.7	48.6	46.8	47.8
2	49.7	47.7	48.0	46.9	47.2

Table 4.6 Average influent and effluent TP concentrations in UASB and HUASB reactors

HRT (days)	Influent TP (mg/L)	Effluent TP (mg/L)				
		Mesophilic UASB	Thermophilic UASB	Mesophilic HUASB	Thermophilic HUASB	
Low strength influent						
5	6.6	17.3	19.9	N/A	N/A	
3	6.6	18.1	20.8	26.8	27.2	
High strength influent						
5	13.3	18.2	19.3	29.3	32.2	
4	11.3	18.1	18.5	23.2	26.7	
3	11.7	15.0	17.7	23.1	27.4	
2	11.6	13.4	17.9	23.9	26.4	

The effluent from the UASB reactor contained higher orthophosphates and nitrogen levels. Under anaerobic conditions, phosphorous accumulating organisms (PAOs) will assimilate fermentation products into storage products within the cells with concomitant release of phosphorous from stored polyphosphates. The nitrogen demand for growth of anaerobic bacteria is almost negligible and if no accumulation of organic matter in the bioreactor occurs, the balance between total nitrogen flow in and out of the reactor should be constant (Metcalf & Eddy, 2003; Parawira et al., 2005). The effluent $\text{NH}_3\text{-N}$ concentration increased and the effluent $\text{NO}_3\text{-N}$ concentration was constant because nitrification did not occur in UASB and HUASB reactors.

4.3 VFA, alkalinity and pH in UASB and HUASB Reactors

The anaerobic reactors generally are affected by the changing of environmental and/or operating conditions. The typical responses in the anaerobic reactor include a decrease in performance, VFA accumulation, pH and alkalinity drop, change of biogas production and composition and sludge washout. The VFA/alkalinity ratio should be lower than 0.3 (Leitao et al., 2006).

During this study, the pH of pharmaceutical wastewater ranged from 4.76 to 6.04. The influent alkalinity was maintained at 1500 to 2000 mg $\text{CaCO}_3\text{/L}$. The pH of pharmaceutical wastewater after adjustment with sodium bicarbonate was approximately 7.48. The influent and effluent pH and alkalinity in UASB and

HUASB reactors during this study are shown in Figure 4.41 and Figure 4.42, respectively.

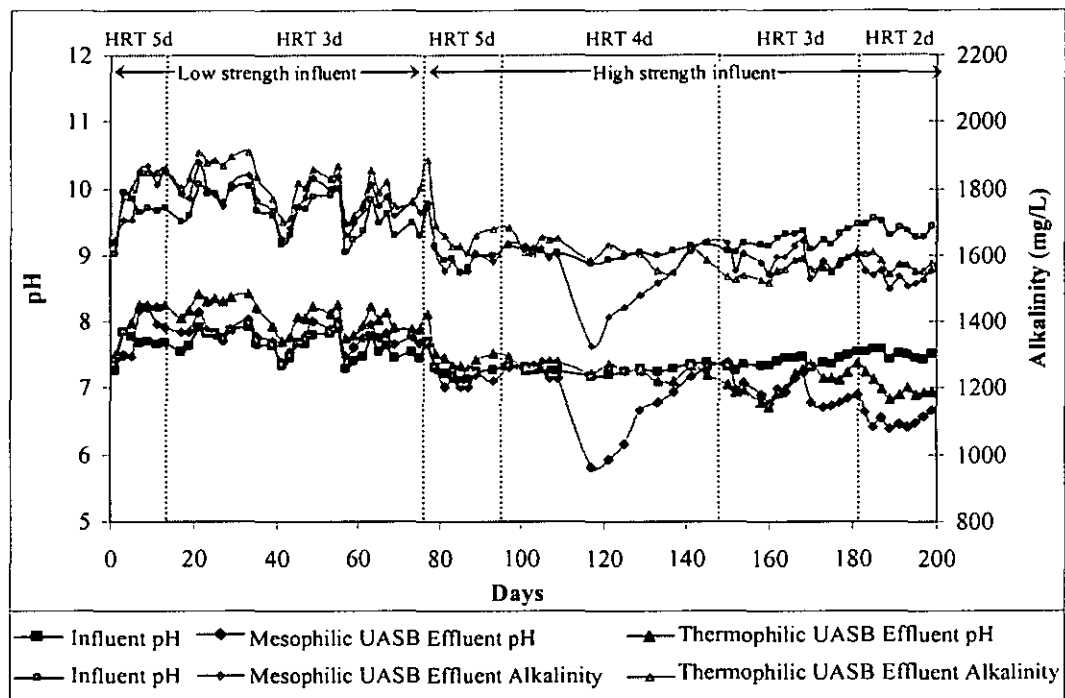


Figure 4.41 Influent and effluent pH and alkalinity in UASB reactors

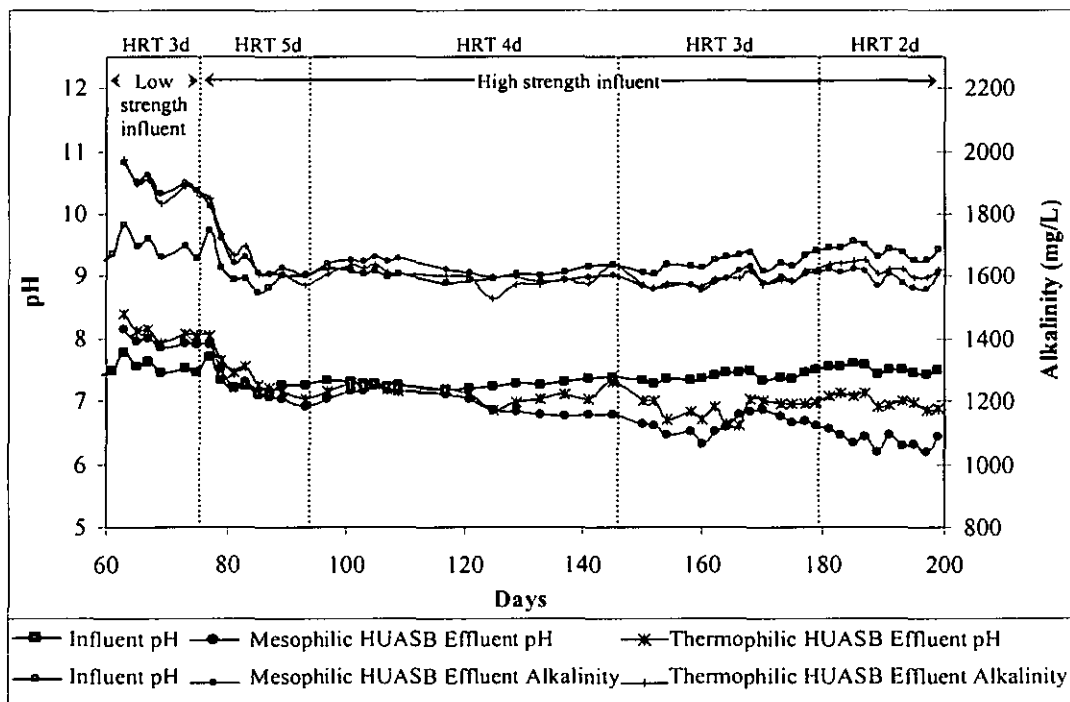


Figure 4.42 Influent and effluent pH and alkalinity in HUASB reactors

In the first 75 days, the UASB reactors were fed with low strength influent (COD 458-526 mg/L) at HRTs of five and three days. The influent pH of the UASB reactors ranged from 7.26 to 7.84 and 7.28 to 7.91, whereas, the influent alkalinity ranged from 1603 to 1787 mg CaCO₃/L and 1609 to 1813 mg CaCO₃/L for HRT of five and three days, respectively. The average effluent pH slightly decreased when the HRT was decreased from five to three days. The average effluent pH decreased from 7.81 to 7.78 and 8.25 to 7.98 for mesophilic and thermophilic UASB reactors, respectively. The effluent alkalinity at HRT of five days ranged from 1644 to 1866 mg CaCO₃/L and 1848 to 1861 mg CaCO₃/L, whereas at HRT of three days, the effluent alkalinity ranged from 1646 to 1875 mg CaCO₃/L and 1696 to 1909 mg CaCO₃/L for mesophilic and thermophilic UASB reactors, respectively.

The HUASB reactors were put in operation 62 days after the UASB reactors. For the first 12 days, the HUASB reactors were fed with low strength wastewater at HRT of three days. The average effluent pH were 7.95 and 8.05, whereas the effluent alkalinity ranged from 1865 to 1964 mg CaCO₃/L and 1833 to 1973 mg CaCO₃/L for mesophilic and thermophilic HUASB reactors, respectively.

The VFA was measured from day 65 and the average influent and effluent VFA concentration in UASB and HUASB reactors during this study is shown in Figure 4.43. At HRT of three days, the average influent VFA was 16.2 mg acetic acid/L. The average effluent VFA in mesophilic reactors was lower than the average effluent VFA in thermophilic reactors. The average effluent VFA in mesophilic and thermophilic UASB reactors were 23.5 mg acetic acid/L and 36.5 mg acetic acid/L, respectively, whereas the average effluent VFA were 29.0 mg acetic acid/L and 55.3 mg acetic acid/L for mesophilic and thermophilic HUASB reactors, respectively.

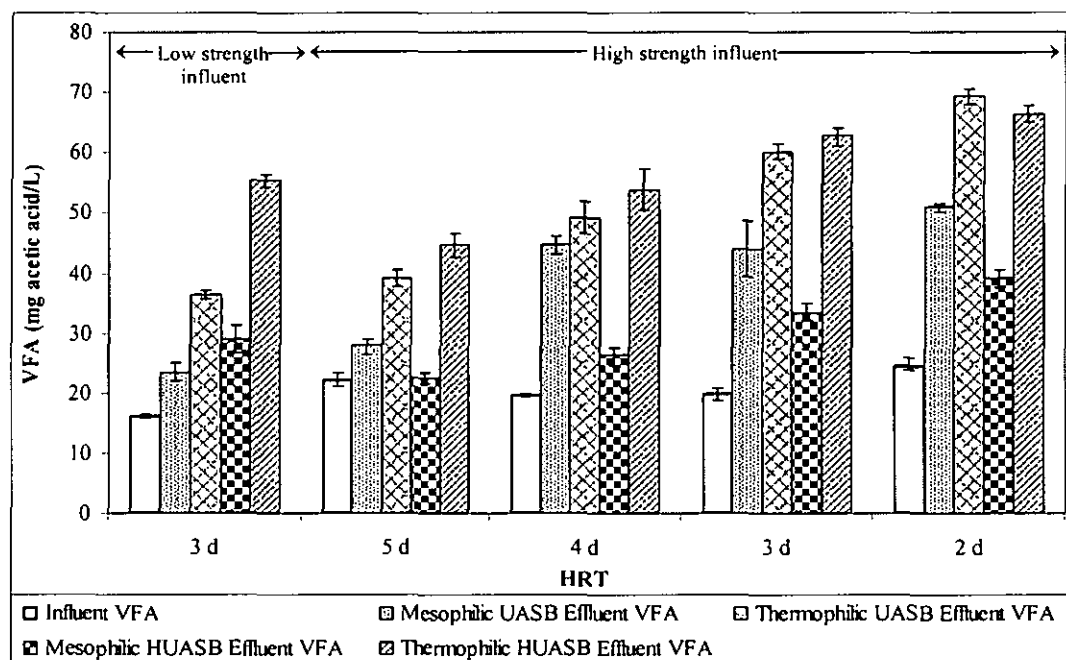


Figure 4.43 Average influent and effluent VFA concentrations in UASB and HUASB reactors

From day 76 to day 199, the UASB and HUASB reactors were fed with high strength wastewater (COD 1770-2217 mg/L) at HRTs of five, four, three and two days. The influent pH and alkalinity in UASB reactors ranged from 7.11 to 7.70 mg CaCO_3/L and 1547 to 1743 mg CaCO_3/L , respectively. On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The effluent VFA sharply increased from 35 to 293 mg acetic acid/L, whereas the effluent pH sharply decreased from 7.16 to 5.81. The pH and alkalinity in the reactor during the upset period was not included in data analysis. After 30 days, the reactor stabilized with pH of 7.28 and alkalinity of 1643 mg CaCO_3/L .

The average effluent pH decreased when the HRT were decreased. The average effluent pH in mesophilic UASB reactor was lower than the average effluent pH in thermophilic UASB reactor. The average effluent pH in mesophilic UASB reactor were 7.18, 7.26, 6.89 and 6.55, whereas in thermophilic UASB reactor, the average effluent pH were 7.50, 7.29, 7.16 and 6.92 at HRTs of five, four, three and two days, respectively. The average effluent alkalinity also decreased when the HRT were

decreased in both of UASB reactors. The average effluent alkalinity in mesophilic UASB reactor were 1600, 1621, 1582 and 1537 mg CaCO_3/L , whereas in thermophilic UASB reactor, the average effluent alkalinity were 1680, 1613, 1570 and 1562 mg CaCO_3/L at HRTs of five, four, three and two days, respectively. The average effluent alkalinity in mesophilic UASB reactor was higher than the average effluent alkalinity in thermophilic UASB reactor at HRTs of four and three days. It seems the reactor was still sensitive due to its previous failure (temperature shock).

The average effluent pH in mesophilic HUASB reactor was lower than the average effluent pH in thermophilic HUASB reactor. The average effluent pH in mesophilic HUASB reactor were 7.25, 6.99, 6.63 and 6.36, whereas in thermophilic HUASB reactor, the average effluent pH were 7.42, 7.12, 6.86 and 6.86 at HRTs of five, four, three and two days, respectively. The average effluent alkalinity also decreased when the HRT were decreased in both of HUASB reactors. The average effluent alkalinity in mesophilic HUASB reactor were 1663, 1621, 1587 and 1595 mg CaCO_3/L , whereas in thermophilic HUASB reactor, the average effluent alkalinity were 1668, 1597, 1592 and 1624 mg CaCO_3/L at HRTs of five, four, three and two days, respectively.

The VFA of high strength influent ranged from 15.7 to 25.3 mg acetic acid/L. At HRT of five days, the average effluent VFA in mesophilic reactors were lower than the average effluent VFA in thermophilic reactors at both UASB and HUASB reactors. The average VFA in mesophilic and thermophilic UASB reactors were 28.0 mg acetic acid/L and 39.2 mg acetic acid/L, respectively, whereas the average VFA were 22.5 mg acetic acid/L and 44.7 mg acetic acid/L for mesophilic and thermophilic HUASB reactors, respectively. The average effluent VFA increased in all reactors when the HRT were decreased, except in mesophilic UASB reactor after it failure. The average effluent VFA increased from 49.3 to 60.2 mg acetic acid/L, 26.5 to 33.3 mg acetic acid/L and 53.8 to 62.8 mg acetic acid/L for thermophilic UASB reactor, the mesophilic and thermophilic HUASB reactors, respectively, when the HRT was decreased from four to three days. Whereas, the average effluent VFA decreased from 44.7 to 44.1 mg acetic acid/L in mesophilic UASB reactor. For the

last 20 days, the reactors were operated at HRT of two days. The average effluent VFA were 51.0, 69.3, 39.2, 66.3 mg acetic acid/L for mesophilic and thermophilic UASB reactors and mesophilic and thermophilic HUASB reactors, respectively.

In their review, Leitaó et al. (2006) reported that methanogenic activity optimally proceed in the pH range of 6.3-7.8. They also reported that the effect of a drastic pH changed in the influent depended on the alkalinity availability in the anaerobic reactor. This behavior occurred because the buffer capacity of the anaerobic reactor sufficed to maintain the pH in the anaerobic reactor in the optimal range. The recovery in the anaerobic process depends on the level and duration of the imposed changed, in addition to the concentration of VFA during the event. The VFA concentrations in the effluent of all reactors were low and the total alkalinity was relatively high. Accordingly, the VFA/bicarbonate alkalinity ratio was always less than 0.3.

4.4 Kinetic Evaluation

Kinetic evaluation is important in the design, development and operation of UASB and HUASB reactors (Bhunia and Ghangrekar, 2008; Buyukkamaci and Filibeli, 2002). The determination of kinetics constants of the reactors was performed by applying three kinetic models to data obtained from the experiments. Based on the biochemistry and microbiology in the anaerobic process, kinetic evaluation deals with operational and environmental factors. Bacterial growth kinetics was based on two fundamental relationships, i.e., growth rate and substrate utilization rate. Various kinetic models reported for biological treatment (including for anaerobic treatment) predominantly based on Monod's equation or its modifications. Different researchers have determined the values of kinetic coefficients by means of regression analysis of experimental data that were generated from lab scale and/or pilot scale studies. Based on previous studies, most kinetic models were non-linear in nature. Therefore, a non-linear regression technique would be more suitable for evaluation of kinetic constants embedded in the models. However, linear regression can also able to yield a set of good estimates, if the non-linear model could be transformed into proper linear form. Three kinetic models i.e. Monod, modified Stover-Kincannon and Grau second-order

were applied in this study and the reactor performance data under steady-state condition for kinetic models analysis are shown in Table 4.7. Monod and modified Stover-Kincannon kinetic models were evaluated for high strength wastewater, whereas Grau second-order kinetic model was evaluated for low strength and high strength wastewater. Due to low R^2 values, the low strength wastewater data was not used in Monod and Stover-Kincannon kinetic models.

The sludge volume and sludge concentration in UASB and HUASB reactors during this study are shown in Figure 4.44 and Figure 4.45, respectively. In the first 75 days, the UASB reactors were fed with low strength influent at HRTs of five and three days. At HRT of five days, the average sludge volumes were 2.42 L and 2.39 L, whereas the average sludge concentrations were 13558 mg VSS/L and 12245 mg VSS/L for mesophilic and thermophilic UASB reactors, respectively. At HRT of three days, the average sludge concentrations were 13922 mg VSS/L and 12914 mg VSS/L and the sludge volumes increased from 2.42 to 2.43 L and 2.39 to 2.40 L for mesophilic and thermophilic UASB reactors, respectively. The HUASB reactors were put in operation 62 days after the UASB reactors. For mesophilic and thermophilic HUASB reactors, the average sludge volumes were 2.36 L and 2.29 L, whereas the average sludge concentrations were 14124 mg VSS/L and 13098 mg VSS/L, respectively.

From day 76 to day 199, the UASB and HUASB reactors were fed with high strength wastewater at HRTs of five, four, three and two days. For mesophilic and thermophilic UASB reactors at HRT of five days, the average sludge volumes were 2.43 L and 2.40 L, whereas the average sludge concentrations were 14438 mg VSS/L and 13668 mg VSS/L, respectively, whereas for mesophilic and thermophilic HUASB reactors, the sludge volumes and concentrations were 2.37 L and 2.31 L and 14736 mg VSS/L and 13428 mg VSS/L, respectively. On day 110, the mesophilic UASB reactor failed due to malfunctioning of the thermostat. The sludge volume and sludge concentration decreased from 2.43 to 2.39 L and 14959 to 12927 mg VSS/L, respectively, due to sludge washout. The sludge data in the reactor during the upset

period was not included in data analysis. After 30 days, the reactor stabilized with sludge volume of 2.37 L and sludge concentration of 13551 mg VSS/L.

Table 4.7 Reactor performance parameters under steady-state condition

HRT (day)	Influent COD (mg/L)	Effluent COD (mg/L)	Sludge bed volume (L)	X (mg/L)	X _e (mg/L)	Influent flow rate (L/day)	SRT (day)
Mesophilic UASB							
5*	487	60	2.42	13558	15	1.00	2218
3*	505	65	2.42	13922	10	1.67	1971
5	2127	158	2.43	14438	16	1.00	2248
4	1989	262	2.41	14424	17	1.25	1597
3	1875	369	2.37	15452	21	1.67	1057
2	1820	478	2.39	16545	26	2.50	614
Thermophilic UASB							
5*	487	95	2.39	12245	12	1.00	2391
3*	505	83	2.39	12914	13	1.67	1449
5	2127	213	2.40	13668	19	1.00	1759
4	1989	329	2.42	14216	30	1.25	913
3	1875	464	2.43	15652	24	1.67	936
2	1820	582	2.43	16701	27	2.50	596
Mesophilic HUASB							
3*	505	61	2.36	14124	12	1.67	1647
5	2127	133	2.36	14736	14	1.00	2534
4	1989	208	2.38	15248	15	1.25	1952
3	1875	270	2.39	16530	19	1.67	1261
2	1820	319	2.40	17412	21	2.50	793
Thermophilic HUASB							
3*	505	172	2.29	13098	15	1.67	1205
5	2127	281	2.30	13428	18	1.00	1816
4	1989	366	2.32	14263	21	1.25	1304
3	1875	382	2.33	15643	21	1.67	1062
2	1820	504	2.33	16493	24	2.50	638

(* low strength wastewater data for Grau second-order kinetic model)

(X is the biomass concentration in the sludge bed; X_e is the biomass concentration of effluent wastewater)

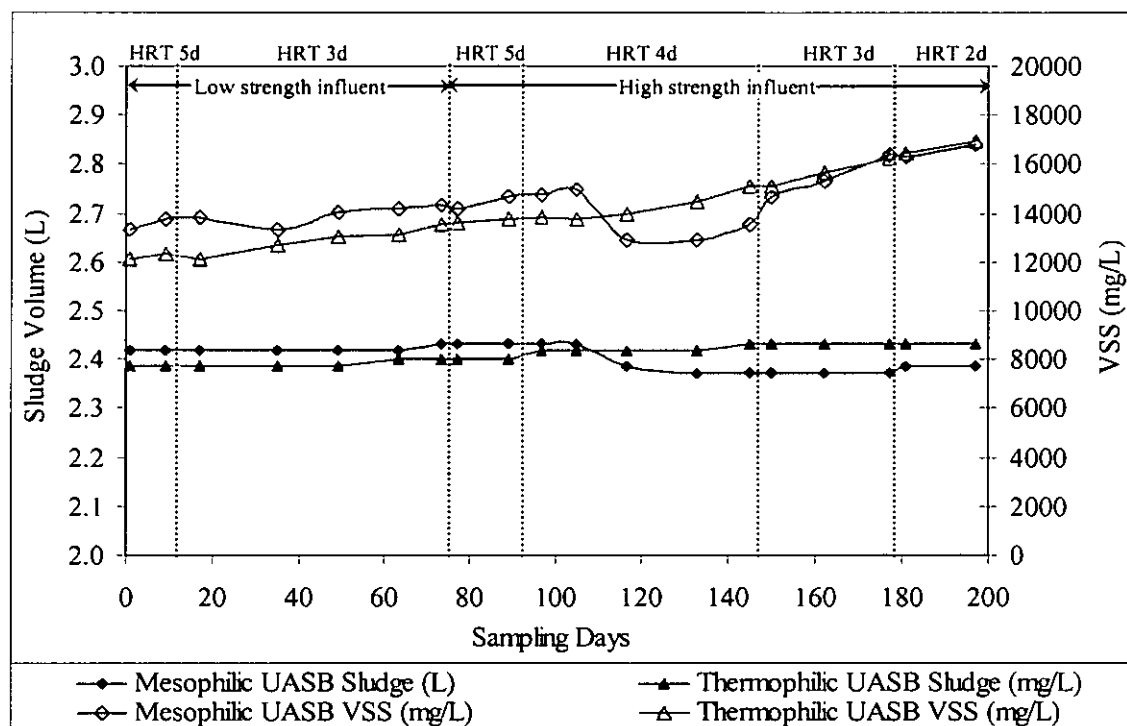


Figure 4.44 Sludge volume and sludge concentration in UASB reactors

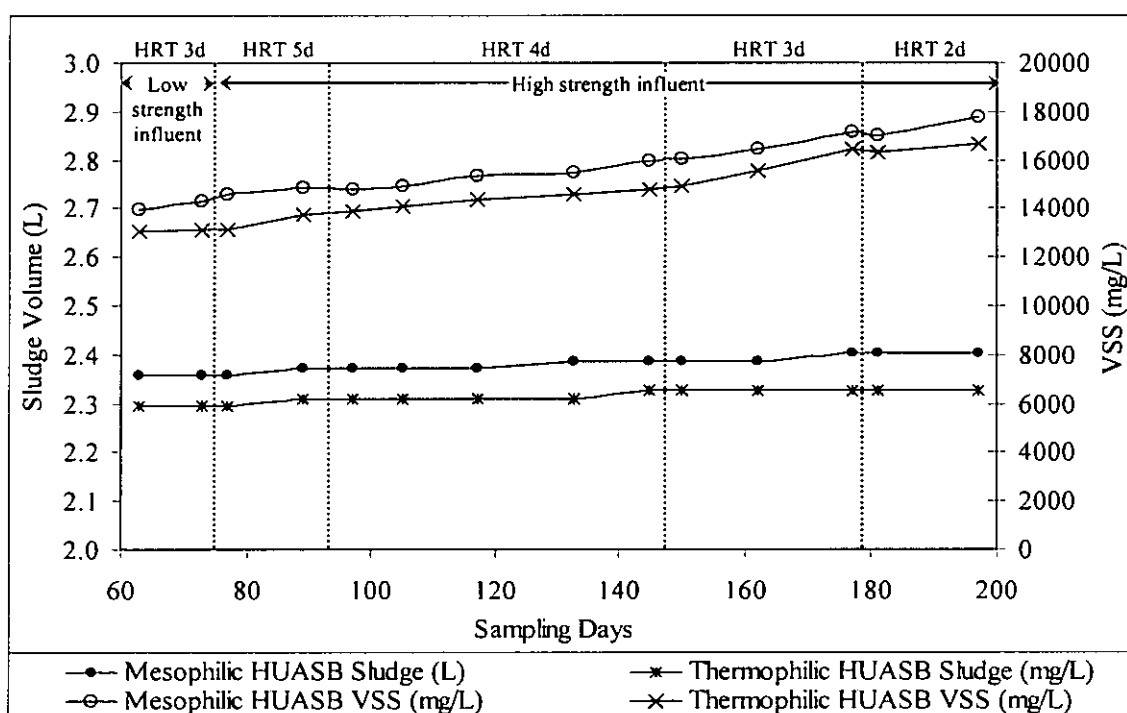


Figure 4.45 Sludge volume and sludge concentration in HUASB reactors

At HRT of four days, the sludge volumes were increased in all reactors, except in mesophilic UASB reactor. The sludge volume increased from 2.42 to 2.43 L, 2.37 to 2.39 L and 2.31 to 2.33 L for thermophilic UASB, mesophilic and thermophilic HUASB reactors, respectively. The average sludge concentration in thermophilic UASB reactor was 14216 mg VSS/L, whereas in the mesophilic and thermophilic HUASB reactors it was 15248 mg VSS/L and 14263 mg VSS/L respectively. The average sludge volumes and sludge concentrations in mesophilic UASB reactors were 2.41 L and 14424 mg VSS/L, respectively.

From day 146 to day 199, the reactors were operated at HRTs of three and two days. In mesophilic UASB reactor, the sludge volume increased from 2.37 to 2.39 L, whereas it was constant in thermophilic UASB reactor. The average sludge concentrations increased from 15452 to 16545 mg VSS/L and 15652 to 16701 mg VSS/L for mesophilic and thermophilic UASB reactors, respectively. In mesophilic HUASB reactor, the sludge volume also increased from 2.39 to 2.40 L, whereas it was constant in thermophilic HUASB reactor. The average sludge concentrations increased from 16530 to 17412 mg VSS/L and 15643 to 16493 mg VSS/L for mesophilic and thermophilic HUASB reactors, respectively.

4.4.1 Application of Monod Kinetic Model

For the UASB and HUASB reactors without biomass recycle, the rate of change of biomass and substrate in the system can be expressed respectively as Eqs. 4.1 and 4.2:

$$\frac{dX}{dt} = \frac{Q}{V_b} \cdot X_o - \frac{Q}{V_b} \cdot X_e + \mu \cdot X - K_d \cdot X \quad (4.1)$$

(Wiesmann et al., 2007)

$$\frac{dS}{dt} = \frac{Q}{V_b} \cdot S_o - \frac{Q}{V_b} \cdot S_e - \frac{\mu \cdot X}{Y} \quad (4.2)$$

(Wiesmann et al., 2007)

where, Q is the flow rate of influent wastewater in L/day; V_b is the volume of sludge bed in L; X_o is the biomass concentration of influent wastewater in mg/L; X_e is the biomass concentration of effluent wastewater in mg/L; X is the biomass concentration

in the sludge bed in mg/L; μ is the specific growth rate in per day; K_d is the endogenous decay coefficient in per day; Y is the cell yield coefficient in mg VSS/mg COD; S_o is the influent substrate concentration in mg/L; and S_e is the effluent substrate concentration in mg/L.

The ratio of total biomass in the reactor to biomass wasting rate is called SRT or referred as mean cell residence time (θ_c). The θ_c is calculated using Eq. 4.3.

$$\theta_c = \frac{V_b \cdot X}{Q \cdot X_e} \quad (4.3)$$

(Metcalf & Eddy, 2003)

Eq. 4.4 shows the specific growth rate (μ)

$$\mu = \frac{\mu_m \cdot S_e}{K_s + S_e} \quad (4.4)$$

(Wiesmann et al., 2007)

If it is presumed that biomass concentration of influent wastewater, X_o , is negligible and at steady state conditions, $\frac{dX}{dt} = 0$ and $\frac{dS}{dt} = 0$, then:

$$X = \frac{Q \cdot Y \cdot \theta_c \cdot (S_o - S_e)}{V_b \cdot (1 + K_d \cdot \theta_c)} \quad (4.5)$$

(Bhunias and Ghangrekar, 2008)

$$S_e = \frac{K_s \cdot (1 + K_d \cdot \theta_c)}{\theta_c \cdot (\mu_m - K_d) - 1} \quad (4.6)$$

(Bhunias and Ghangrekar, 2008)

Eqs. 4.5 and 4.6 are nonlinear in nature, hence it is indispensable to transform them to linearized forms. Two different linearized equations can be framed to obtain Y and K_d values, which are

$$\frac{Q \cdot (S_o - S_e)}{V_b \cdot X} = \frac{1}{Y} \cdot \frac{1}{\theta_c} + \frac{1}{Y} \cdot K_d \quad (4.7)$$

(Bhunias and Ghangrekar, 2008)

$$\frac{1}{\theta_c} = Y \cdot \frac{Q \cdot (S_o - S_e)}{V_b \cdot X \cdot \theta_c} - K_d \quad (4.8)$$

(Bhunia and Ghangrekar, 2008)

To obtain the estimates of μ_m and K_s , linear regression is applied on the linearized equation derived from substituting Eq. 4.6 into Eq. 4.2.

$$\frac{V_b \cdot S_e \cdot X}{Q \cdot (S_o - S_e)} = \frac{Y}{\mu_m} \cdot S_e + \frac{Y \cdot K_s}{\mu_m} \quad (4.9)$$

(Bhunia and Ghangrekar, 2008)

The other linear form of linearized equation reported in the literature for estimation of μ_m and K_s are as follow

$$\frac{X \cdot V_b}{Q \cdot (S_o - S_e)} \cdot \frac{1}{Y} = \frac{K_s}{\mu_m} \cdot \frac{1}{S_e} + \frac{1}{\mu_m} \quad (4.10)$$

(Bhunia and Ghangrekar, 2008)

$$\frac{Q \cdot (S_o - S_e) \cdot Y}{V_b \cdot X} = \mu_m - K_s \frac{Q \cdot (S_o - S_e) \cdot Y}{X \cdot V_b \cdot S_e} \quad (4.11)$$

(Bhunia and Ghangrekar, 2008)

In order to determine the Monod kinetic model coefficients (Y , K_d , μ_m and K_s), the data (high strength influent) shown in Table 4.7 were plotted in Figure 4.46 and Figure 4.47. The values of Y and K_d were determined based on the linearized equation (Eq. 4.7). The values of Y and K_d were calculated from the intercept and slope of the linearized graphs (Figure 4.46). The values of μ_m and K_s were determined based on the linearized equation (Eq. 4.9). The values of μ_m and K_s were calculated from the intercept and slope of the linearized graphs and were shown in Figure 4.47. Table 4.8 shows the Monod kinetic model coefficients obtain in this study for the reactors. High R^2 values ($R^2 > 0.9$) were obtained for Y and K_d determinations for all reactors and μ_m and K_s determinations for UASB reactors. However, the R^2 values were lower for μ_m and K_s determinations (0.7023 and 0.6797) for HUASB reactors.

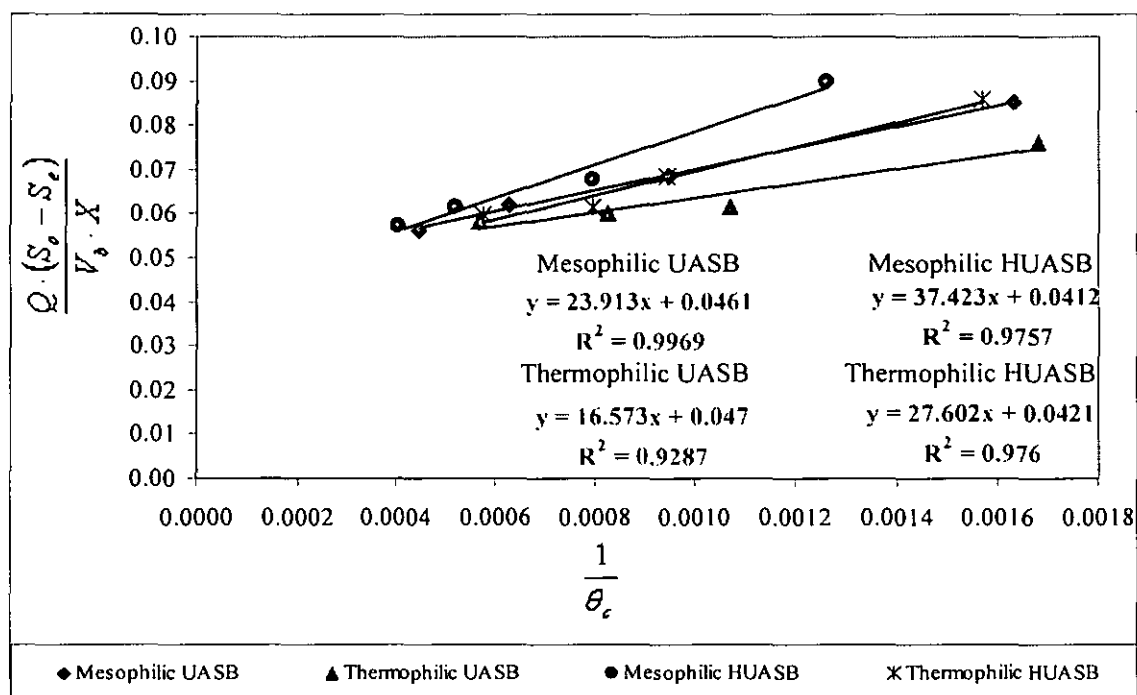
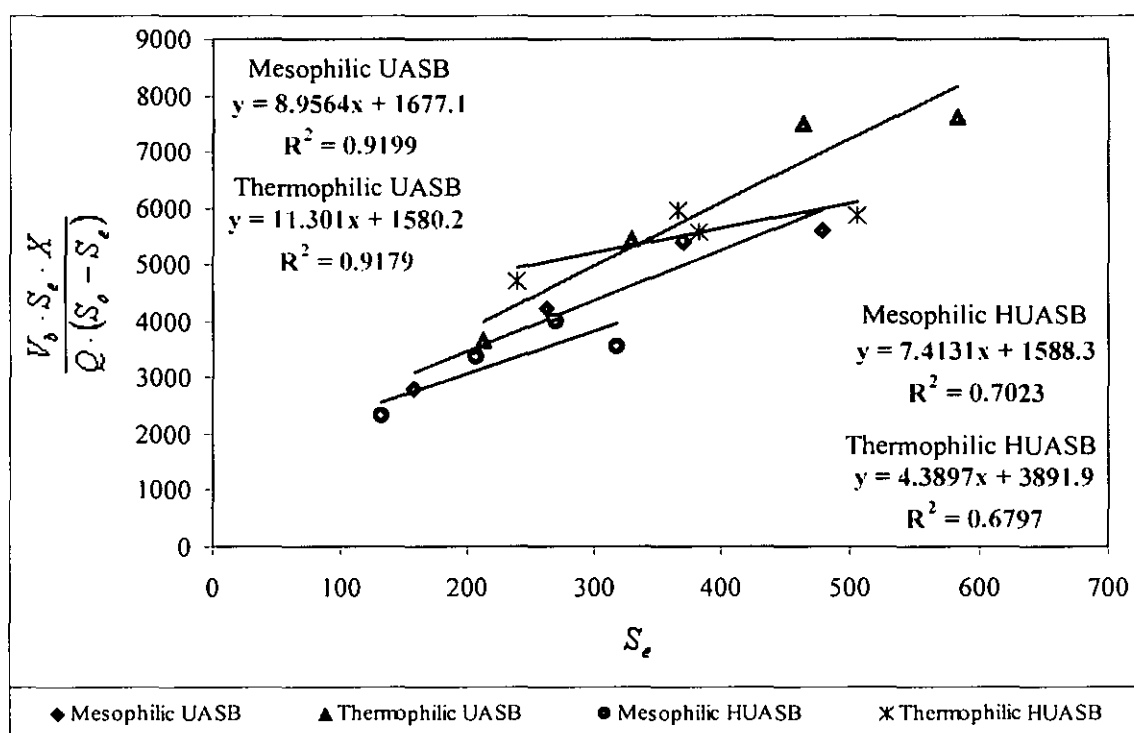
Figure 4.46 Determination of Monod kinetic model coefficients, Y and K_d valuesFigure 4.47 Determination of Monod kinetic model coefficients, μ_m and K_s values

Table 4.8 Monod kinetic model coefficients

Reactor	Y	K_d (per day)	R^2	μ_m (per day)	K_s (mg/L)	R^2
Mesophilic UASB	0.042	0.00193	0.9969	0.00467	187.3	0.9199
Thermophilic UASB	0.060	0.00284	0.9287	0.00534	139.8	0.9179
Mesophilic HUASB	0.027	0.00110	0.9757	0.00371	220.6	0.7023
Thermophilic HUASB	0.036	0.00153	0.9760	0.00825	886.6	0.6797

(Y in mg VSS/mg COD)

4.4.2 Application of Modified Stover-Kincannon Kinetic Model

Stover-Kincannon is one of the most widely used mathematical model for determining the kinetic constant in biofilm reactors. The Stover-Kincannon model considers the organic substance removal rate as a function of organic loading rate at steady state as in Eq. 4.12

$$\frac{dS}{dt} = \frac{Q}{V} \cdot (S_o - S_e) \quad (4.12)$$

(Buyukkamaci and Filibeli, 2002; Kapdan, 2005)

Equations of the modified Stover-Kincannon model are follows:

$$\frac{dS}{dt} = \frac{U_{\max} \cdot \left(\frac{Q \cdot S_i}{V} \right)}{K_B + \left(\frac{Q \cdot S_o}{V} \right)} \quad (4.13)$$

(Buyukkamaci and Filibeli, 2002; Kapdan, 2005)

where, K_B saturation value constant (modified Stover-Kincannon) in g/L·day; U_{\max} maximum substrate removal rate (modified Stover-Kincannon), in g/L·day

Eq. 4.14 obtained from linearization of Eqs. 4.12 and 4.13 as follows:

$$\frac{V}{Q \cdot (S_o - S_e)} = \frac{K_B}{U_{\max}} \cdot \frac{V}{Q \cdot S_o} + \frac{1}{U_{\max}} \quad (4.14)$$

(Buyukkamaci and Filibeli, 2002; Kapdan, 2005)

In order to determine the modified Stover-Kincannon kinetic model coefficients (K_B and U_{max}), the data (high strength influent) shown in Table 4.7 were plotted in Figure 4.48. The values of K_B and U_{max} were determined based on the linearized equation (Eq. 4.14). The values of K_B and U_{max} were calculated from the intercept and slope of the linearized graphs. Table 4.9 shows the modified Stover-Kincannon kinetic model coefficients obtain in this study for the reactors. High R^2 values ($R^2 > 0.9$) were obtained for K_B and U_{max} determinations for all reactors.

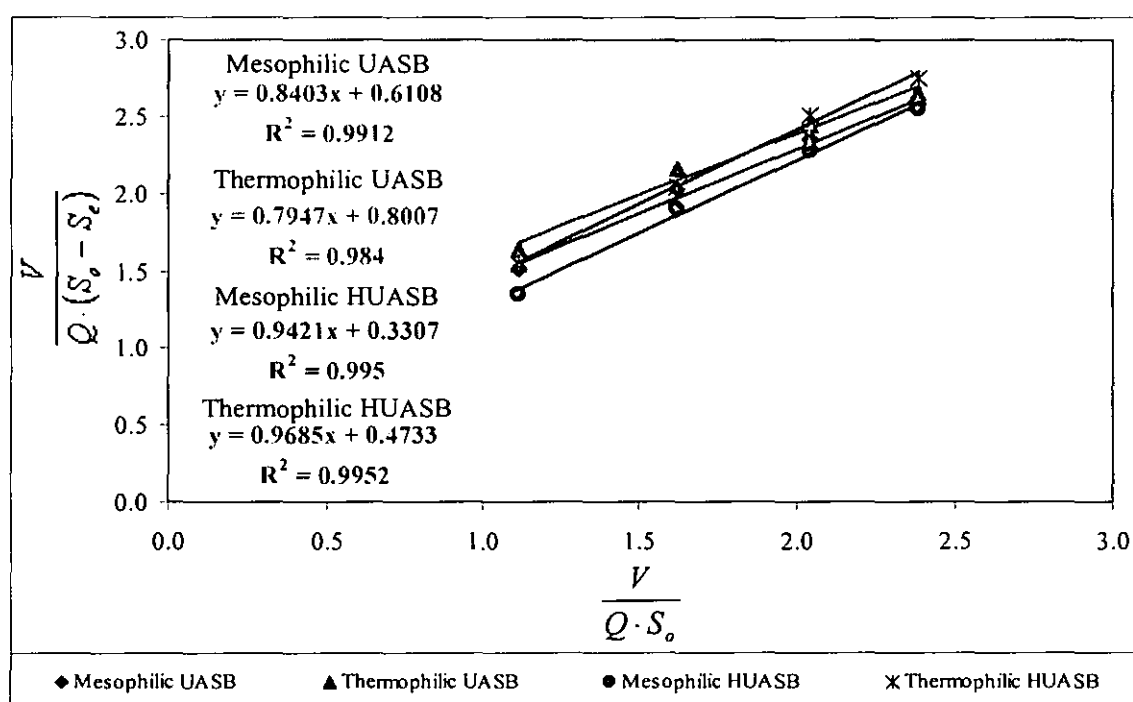


Figure 4.48 Determination of modified Stover-Kincannon kinetic model coefficients, K_B and U_{max} values

Table 4.9 Modified Stover-Kincannon kinetic model coefficients

Reactor	K_B (g/L·day)	U_{max} (g/L·day)	R^2
Mesophilic UASB	1.376	1.637	0.9912
Thermophilic UASB	0.993	1.2489	0.984
Mesophilic HUASB	2.849	3.024	0.995
Thermophilic HUASB	2.046	2.113	0.9952

4.4.3 Application Grau Second-order Multi-component Substrate Removal Kinetic Model

The general equation of a second order kinetic model used for predicting the behaviour of reactors for estimating kinetic coefficients is given in Eq. 4.15.

$$\frac{dS}{dt} = K_{s2} \cdot X \cdot \left(\frac{S_e}{S_o} \right)^2 \quad (4.15)$$

(Metcalf & Eddy, 2003)

If Eq. 4.15 is integrated ($S = S_o$ to S_e ; and $t = 0$ to θ_H), the linearized Eq. 4.16 will be obtained:

$$\frac{S_o \cdot \theta_H}{S_o - S_e} = \theta_H + \frac{S_o}{K_{s2} \cdot X} \quad (4.16)$$

(Bhunia and Ghangrekar, 2008)

If the second part of the right hand side in Eq. 4.16 is a constant “ a ”, Eq. 4.17 will be obtained

$$\frac{S_o \cdot \theta_H}{S_o - S_e} = a + b \cdot \theta_H \quad (4.17)$$

(Bhunia and Ghangrekar, 2008)

where, the substrate removal kinetic constant $a = \frac{S_o}{K_{s2} \cdot X}$ and the coefficient b in

Eq. 4.17 is close to one and generally reflects the impracticality of attaining a zero value of COD. The substrate removal efficiency is expressed as $\frac{S_o - S_e}{S_o}$ and is

symbolized as E . Therefore, the final equation of Grau kinetic model can be written as

$$\frac{\theta_H}{E} = a + b \cdot \theta_H \quad (4.18)$$

(Bhunia and Ghangrekar, 2008)

In order to determine the kinetic coefficients (a , b and k_{s2}) applying Eq. 4.18, a graph can be plotted with θ_H versus $\frac{\theta_H}{E}$. The values a and b are calculated from the intercept and slope of the straight line.

In order to determine the kinetic coefficients (a , b), the data set shown Table 4.7 was plotted in Figure 4.49. The values of a and b were calculated from the intercept and slope of the linearized graph. Table 4.10 shows the values of kinetic parameter obtain in this study for the reactors. High R^2 values ($R^2 > 0.9$) were obtained for a and b determinations for all reactors.

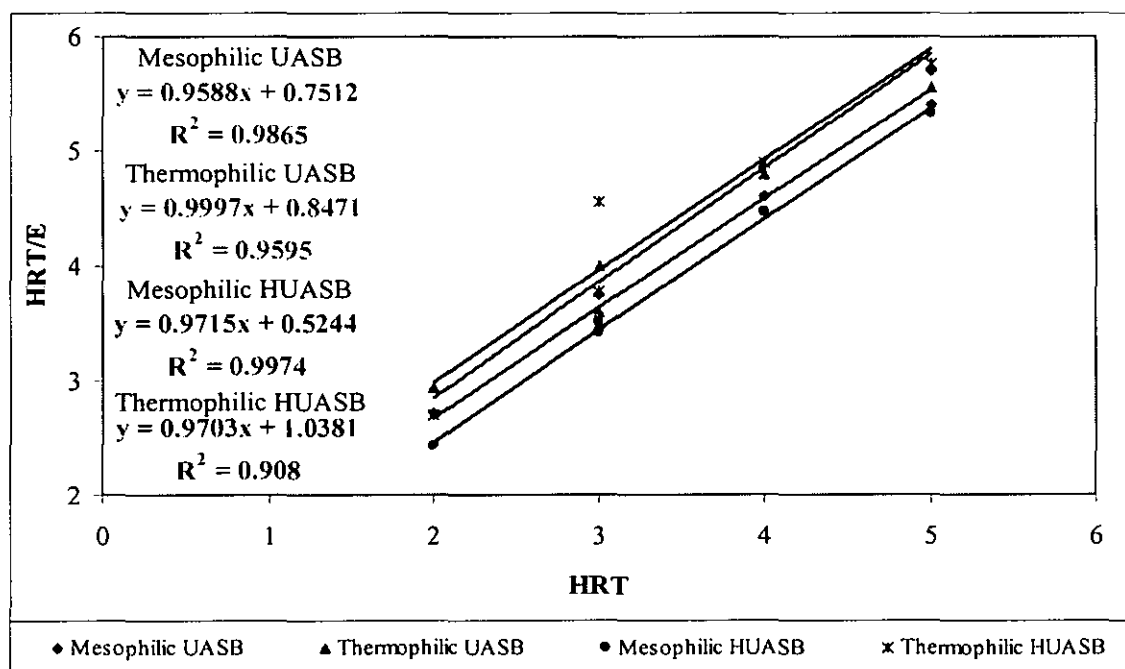


Figure 4.49 Determination of Grau second-order kinetic model coefficients

Table 4.10 Grau second-order kinetic model coefficients

Reactor	a (per day)	b	R^2
Mesophilic UASB	0.7512	0.9588	0.9865
Thermophilic UASB	0.8417	0.9997	0.9595
Mesophilic HUASB	0.5255	0.9715	0.9974
Thermophilic HUASB	1.0381	0.9703	0.908

4.4.4 Evaluation of the Kinetic Models

Table 4.11, Table 4.12 and Table 4.13 show the comparisons of Monod, modified Stover-Kincannon and Grau second-order kinetic model coefficients, respectively. The Monod model is widely used for UASB reactors and other industrial biological reactors. The Monod kinetic model has been applied to anaerobic treatment of various type of wastewater, including synthetic wastewater (Bhunia and Ghangrekar, 2008), simulated textile wastewater (Isik and Sponza, 2005), municipal wastewater (Singh and Viraraghavan, 2002) and POME wastewater (Zinatizadeh et al., 2006).

The modified Stover-Kincannon kinetic model has been applied to mesophilic and thermophilic AF for synthetic starch wastewater (Ahn and Forster, 2000), mesophilic HUASB for synthetic molasses wastewater (Buyukkamaci and Filibeli, 2002), mesophilic UASB for textile wastewater (Isik and Sponza, 2005) and mesophilic UAFB for formaldehyde and textile wastewater (Priya et al., 2009; Sandhya and Swaminathan, 2006). The maximum COD removal rate (U_{max}) and saturation value constant (K_B) in this study were lower than modified Stover-Kincannon kinetic model coefficients that were obtained by Ahn and Foster (2000), Buyukkamaci and Filibeli (2002), Isik and Sponza (2005) and Sandhya and Swaminathan (2006). However, the values of U_{max} and K_B in this study were similar with kinetic model coefficients that were obtained by Priya et al. (2009).

The Grau second-order kinetic model has been applied successfully to anaerobic treatment of various type of wastewater, including synthetic wastewater (Bhunia and Ghangrekar, 2008), poultry slaughterhouse wastewater (Debik and Coskun, 2009), simulated textile wastewater (Isik and Sponza, 2005), synthetic *para*-nitrophenol wastewater (Kuscu and Sponza, 2009) and simulated synthetic coal (Ramakrishnan and Gupta, 2008). The values of a in this study were similar with the values of a that were obtained by Bhunia and Ghangrekar (2008) and Isik and Sponza (2005).

Table 4.11 Comparison of Monod kinetic model coefficients

Wastewater	Type of reactors	Influent COD	HRT	Kinetic parameters				References
Monod				Y	K_d	μ_m	K_s	
Pharmaceutical	Mesophilic UASB	1820-2127 mg/L	2-5 d	0.042	0.00193	0.00467	187.3	This study
Pharmaceutical	Thermophilic UASB	1820-2127 mg/L	2-5 d	0.060	0.00284	0.00534	139.8	This study
Pharmaceutical	Mesophilic HUASB	1820-2127 mg/L	2-5 d	0.027	0.00110	0.00371	220.6	This study
Pharmaceutical	Thermophilic HUASB	1820-2127 mg/L	2-5 d	0.036	0.00153	0.00825	886.6	This study
Synthetic	UASB	300-2000	4-8 h	0.083	0.006	0.058	226.1	(Bhunja and Ghangrekar, 2008)
Simulated textile	Mesophilic UASB	4214 mg/L	6-100 h	0.125	0.0065	0.105	>4000	(Isik and Sponza, 2005)
Municipal	Mesophilic UASB	250-550 mg/L	3-48 h	0.422	0.0033	0.16	601	(Singh and Viraraghavan, 2002)
POME	Mesophilic UASFF	5260-34725 mg/L	1-6 d	0.174	N/S	0.287	982	(Zinatizadeh et al., 2006)

(Y in mg VSS/mg COD; K_d in per day; μ_m in per day; K_s in per day)

Table 4.12 Comparison of modified Stover-Kincannon kinetic model coefficients

Wastewater	Type of reactors	Influent COD	HRT	Kinetic parameters		References
Modified Stover-Kincannon				U_{max} (g/L·d)	K_B (g/L·d)	
Pharmaceutical	Mesophilic UASB	1820-2127 mg/L	2-5 d	1.637	1.376	This study
Pharmaceutical	Thermophilic UASB	1820-2127 mg/L	2-5 d	1.2489	0.993	This study
Pharmaceutical	Mesophilic HUASB	1820-2127 mg/L	2-5 d	3.024	2.849	This study
Pharmaceutical	Thermophilic HUASB	1820-2127 mg/L	2-5 d	2.113	2.046	This study
Synthetic starch	Mesophilic AF	2000-4000 mg/L	24 h	49.8	50.6	(Ahn and Forster, 2000)
Synthetic starch	Thermophilic AF	2000-4000 mg/L	24 h	66.7	70.2	(Ahn and Forster, 2000)
Synthetic molasses	Mesophilic HUASB	1-10 g COD/L·d	0.5-2 d	83.3	186.23	(Buyukkamaci and Filibeli, 2002)
Poultry slaughterhouse	Static Anaerobic Sludge Bed Reactor	6880±1400 mg/L	36-60	121.71	130.28	(Debik and Coskun, 2009)
Poultry slaughterhouse	Static Granular Bed Reactor	6880±1400 mg/L	36-60	164.48	177.21	(Debik and Coskun, 2009)
Simulated textile	Mesophilic UASB	4214 mg/L	6-100 h	8.211	7.501	(Isik and Sponza, 2005)
Synthetic dye	Upflow anaerobic packed bed reactor	1-8 g/L·d	N/S	12.9	37.9	(Kapdan, 2005)
Industrial pig farming	Anaerobic bioreactor	3150 mg/L	0.6-10 d	80.9	91.582	(Kosinska and Miskiewicz, 2009)
Synthetic <i>para</i> -nitrophenol	AMBR	3000 mg/L	1-10.38 d	29.49	31.55	(Kuscu and Sponza, 2009)
Formaldehyde	Mesophilic UAFB	10976-11840 mg/L	6-24 h	3.4	4.6	(Priya et al., 2009)
Textile	Mesophilic UAFB	1835-3828 mg/L	9.9-23.76 h	31.69	45.37	(Sandhya and Swaminathan, 2006)

Table 4.13 Comparison of Grau second-order kinetic model coefficients

Wastewater	Type of reactors	Influent COD	HRT	Kinetic parameters		References
Grau second-order				<i>a</i> (per d)	<i>b</i>	
Pharmaceutical	Mesophilic UASB	1820-2127 mg/L	2-5 d	0.7512	0.9588	This study
Pharmaceutical	Thermophilic UASB	1820-2127 mg/L	2-5 d	0.8417	0.9997	This study
Pharmaceutical	Mesophilic HUASB	1820-2127 mg/L	2-5 d	0.5255	0.9715	This study
Pharmaceutical	Thermophilic HUASB	1820-2127 mg/L	2-5 d	1.0381	0.9703	This study
Synthetic	UASB	300-2000	4-8 h	0.558	1.043	(Bhunia and Ghangrekar, 2008)
Poultry slaughterhouse	Static Anaerobic Sludge Bed Reactor	6880±1400 mg/L	36-60 h	0.098	1.100	(Debik and Coskun, 2009)
Poultry slaughterhouse	Static Granular Bed Reactor	6880±1400 mg/L	36-60 h	0.173	1.155	(Debik and Coskun, 2009)
Simulated textile	Mesophilic UASB	4214 mg/L	6-100 h	0.562	1.095	(Isik and Sponza, 2005)
Synthetic <i>para</i> -nitrophenol	AMBR	3000 mg/L	1-10.38 d	0.0958	1.071	(Kuscu and Sponza, 2009)
Simulated synthetic coal	Mesophilic HUASB	2240	18-36 h	0.0783	0.9645	(Ramakrishnan and Gupta, 2008)

Bhunia and Ghangrekar (2008) reported that the Grau second-order kinetic was found as the best class of fit for wide range of data set in UASB reactor. The value of a and b were 0.558 and 1.043, respectively, in UASB reactor that was treating synthetic wastewater in the range of 300-4000 mg COD/L. Isik and Sponza (2005) reported that Grau second-order and modified Stover-Kincannon kinetic models were found to be more suitable than Monod, Contois and first-order kinetic models in mesophilic UASB reactor.

Figure 4.50 to Figure 4.53 show the comparisons of the measured and predicted COD concentration in UASB and HUASB reactors. In mesophilic and thermophilic UASB reactors, high R^2 values ($R^2 > 0.9$) were obtained in the comparisons of measured and predicted effluent COD for modified Stover-Kincannon and Grau second-order kinetic models. They indicated high correlations between the measured and predicted effluent COD data and the linear regression lines. However, the R^2 values were lower for Monod kinetic model in mesophilic and thermophilic UASB reactors (0.8165 and 0.8065). In mesophilic UASB reactor, the measured and predicted effluent COD values were similar based on linear regression equations for modified Stover-Kincannon ($y = 0.9923x + 3.4313$) and Grau second-order ($y = 0.9334x + 3.6452$) kinetic models (Figure 4.50). However, the predicted effluent COD value was higher than the measured effluent COD value in Monod kinetic model ($y = 1.2144x - 55.085$).

In thermophilic UASB reactor, the measured and predicted effluent COD value were similar based on linear regression equation only for modified Stover-Kincannon ($y = 0.9923x + 3.4313$) kinetic model (Figure 4.51). The predicted effluent COD value was higher than the measured effluent value in Monod kinetic model ($y = 1.2144x - 55.085$) and the predicted effluent COD value was lower than the measured effluent COD value in Grau second-order kinetic model ($y = 0.8605x + 45.11$).

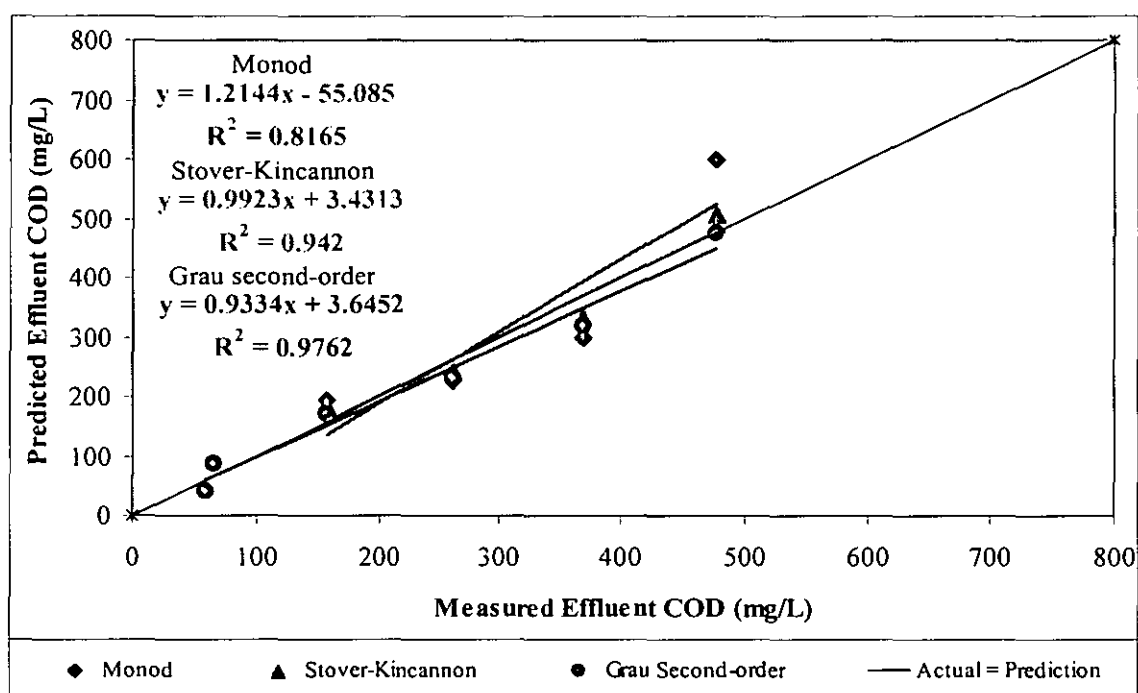


Figure 4.50 Comparison of the measured and predicted effluent COD in mesophilic UASB reactor

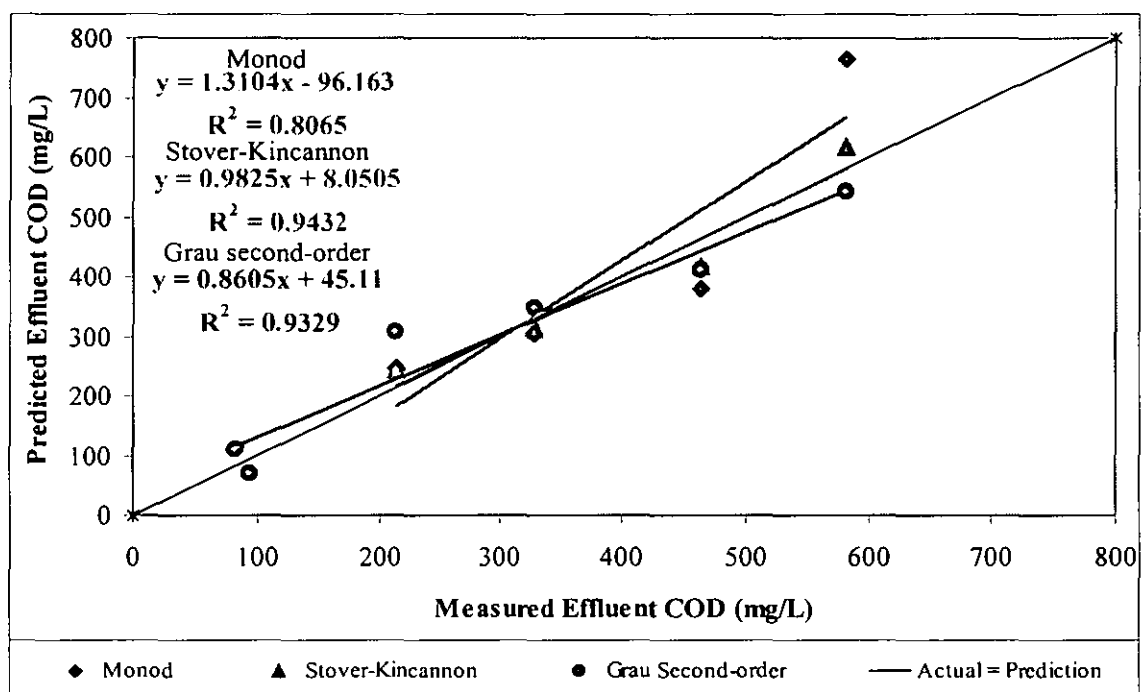


Figure 4.51 Comparison of the measured and predicted effluent COD in thermophilic UASB reactor

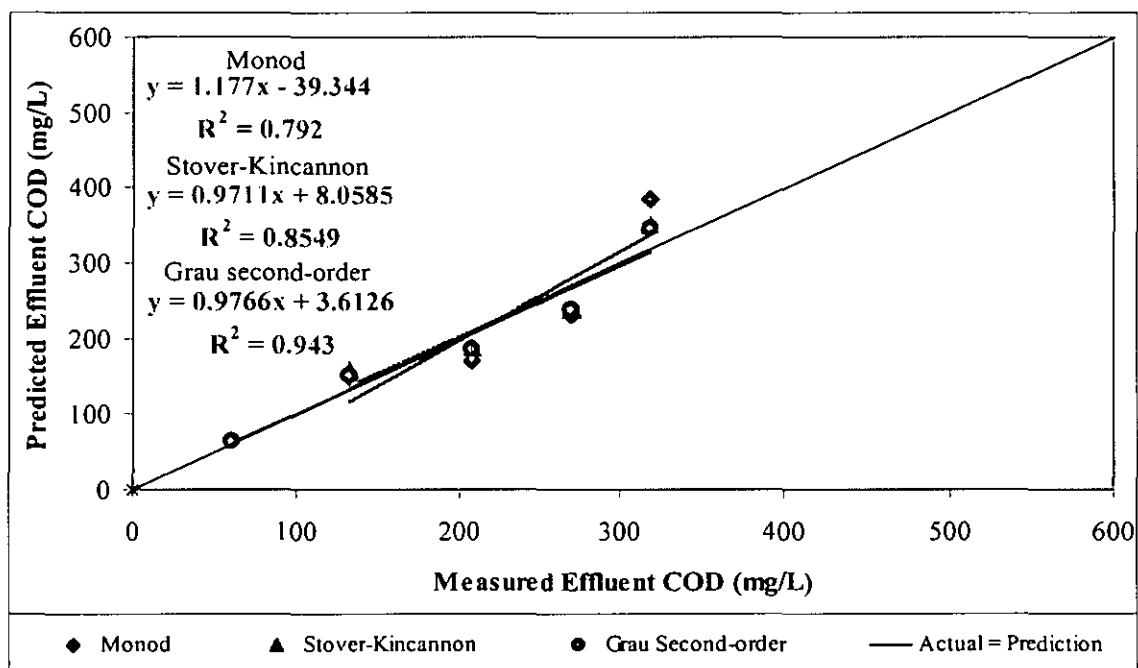


Figure 4.52 Comparison of the measured and predicted effluent COD in mesophilic HUASB reactor

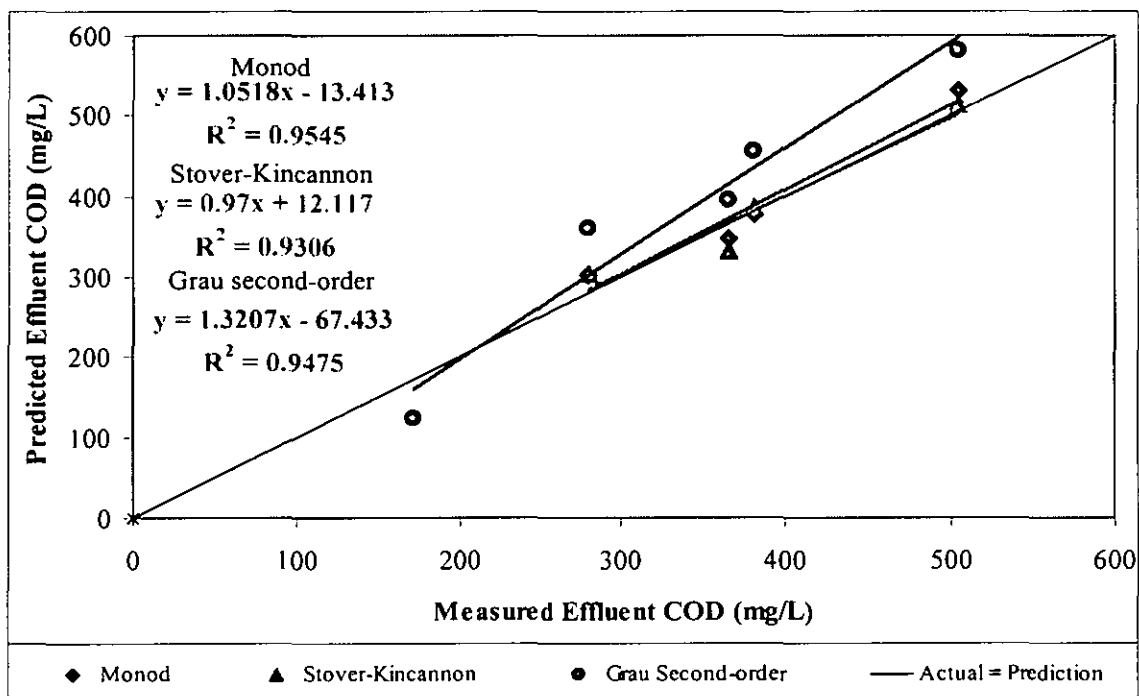


Figure 4.53 Comparison of the measured and predicted effluent COD in thermophilic HUASB reactor

In mesophilic HUASB reactor, high R^2 value ($R^2 > 0.9$) was obtained in the comparison of measured and predicted effluent COD for Grau second-order kinetic model. It indicated high correlation between the measured and predicted effluent COD data and the linear regression line. However, the R^2 values were lower for Monod and modified Stover-Kincannon kinetic model (0.792 and 0.8549). The measured and predicted effluent COD values were similar based on linear regression equations for modified Stover-Kincannon ($y = 0.9711x + 8.0585$) and Grau second-order ($y = 0.9766x + 3.6126$) kinetic models (Figure 4.52). However, the predicted effluent COD value was higher than the measured effluent COD value in Monod kinetic model ($y = 1.177x - 39.344$).

In thermophilic HUASB reactor, high R^2 values ($R^2 > 0.9$) were obtained in the comparisons of measured and predicted effluent COD for all kinetic models. They indicated high correlations between the measured and predicted effluent COD data and the linear regression lines. The measured and predicted effluent COD values were similar based on linear regression equations for Monod ($y = 1.0518x - 13.413$) and modified Stover-Kincannon ($y = 0.97x + 12.117$) kinetic models (Figure 4.53). The predicted effluent COD value was higher than the measured effluent value in Grau second-order kinetic model ($y = 1.3207x - 67.433$).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The biological wastewater treatment study was performed to treat non-penicillin pharmaceutical wastewater. The study was conducted in two phases. The Phase I study observed the performance of semi-anaerobic and aerobic reactors in treating non-penicillin pharmaceutical wastewater. The Phase II was carried out on anaerobic treatment processes. Based on the performance observation of semi-anaerobic and aerobic reactors, the following conclusions can be drawn:

- a. Train 1 (SABR-ASP reactor) achieves higher COD removal in treating the high strength wastewater (COD 1953 mg/L); however, Train 2 (ASP reactor) achieves higher COD removal in treating the low strength wastewater (COD 635 mg/L).
- b. The aerobic biomass from a sewage treatment plant can be successfully used as seed biomass in aerobic and semi-anaerobic reactors in treating non-penicillin pharmaceutical wastewater.

The objective of this study was to evaluate the performance of mesophilic and thermophilic UASB and HUASB reactors in treating non-penicillin pharmaceutical wastewater. The reactors were seeded with sludge from an aerobic domestic sewage treatment plant. The pharmaceutical wastewater was very fluctuative in COD and BOD₅ concentrations. The reactors were fed with low strength influent (COD 458-526 mg/L) and high strength influent (COD 1770-2217 mg/L). Based on the performance evaluation of mesophilic and thermophilic UASB and HUASB reactors, the following conclusions can be drawn:

- a. The HUASB reactors are significantly more efficient in COD removal than the UASB reactors. The UASB and HUASB reactors showed higher COD removals in treating the high strength wastewater.

- b. The concentrations of $\text{NH}_3\text{-N}$ and total phosphorous increase, whereas the concentration of $\text{NO}_3\text{-N}$ remains constant and concentration of TKN slightly reduces.

This study evaluated the effect of HRT and temperature on the performance of UASB and HUASB reactors. The reactors were operated under mesophilic ($35\pm 2^\circ\text{C}$) and thermophilic ($55\pm 2^\circ\text{C}$) temperatures and HRTs of five, four, three and two days. Based on the evaluation of the operation condition effect in mesophilic and thermophilic UASB and HUASB reactors, the following conclusions can be drawn:

- a. The reactor performance is significantly affected by type of reactors, HRT and temperature.
- b. Mesophilic UASB and HUASB reactors achieve higher COD and BOD_5 removals than both thermophilic reactors in treating pharmaceutical wastewater.
- c. The COD and BOD_5 removals decrease when the HRT was decreased.
- d. The highest average COD and BOD_5 removals are achieved by the mesophilic HUASB reactor treating high strength pharmaceutical wastewater at HRT of five days (average OLR 0.43 g COD/L-day); average COD removal is 90%, average effluent COD is 133 mg/L, average BOD_5 removal is 97% and average effluent BOD_5 is 51 mg/L.
- e. The lowest average COD and BOD_5 removals are achieved by the thermophilic UASB reactor at HRT of two days. The average COD and BOD_5 removals are 68% and 76%, respectively, whereas the average COD and BOD_5 concentrations are 582 mg/L and 299 mg/L, respectively.

Three kinetics models i.e. Monod, modified Stover-Kincannon and Grau second-order were applied in this study to determine the kinetics of pharmaceutical wastewater treatment using UASB and HUASB reactors. The results of kinetic model analysis indicate:

- a. Grau second-order fits well for estimates of kinetic coefficients in all reactors. High R^2 values ($R^2 > 0.9$) were obtained for a and b determinations for all reactors.

- b. Among the three kinetic models, Grau second order model is observed to be the preeminent model for predicting the performance of UASB and HUASB reactors. In mesophilic and thermophilic UASB reactors, the values of a are 0.8822 and 0.8471 per day and the values of b are 0.9111 and 0.9997, respectively. In mesophilic and thermophilic HUASB reactors, the values of a are 0.5244 and 0.8767 per day and the values of b are 0.9715 and 1.029, respectively.
- c. In Monod kinetic model, high R^2 values ($R^2 > 0.9$) are obtained for Y and K_d determinations for all reactors and μ_m and K_s determinations for UASB reactors. However, the R^2 values are lower for μ_m and K_s determinations (0.7023 and 0.6797) for HUASB reactors. In mesophilic UASB reactor, the values of Y and K_d are 0.042 mg VSS/mg COD and 0.00193 per day, whereas in thermophilic UASB reactor, the values of Y and K_d are 0.060 mg VSS/mg COD and 0.00284 per day, respectively. The values of μ_m and K_s are 0.00467 per day and 187.3 mg/L in mesophilic UASB reactor, while in thermophilic UASB reactor, the values of μ_m and K_s are 0.00534 per day and 139.8 mg/L, respectively. In mesophilic HUASB reactor, the values of Y and K_d are 0.027 mg VSS/mg COD and 0.00110 per day, whereas in thermophilic HUASB reactor, the values of Y and K_d are 0.036 mg VSS/mg COD and 0.00153 per day, respectively. The values of μ_m and K_s are 0.00371 per day and 220.6 mg/L in mesophilic HUASB reactor, whereas in thermophilic HUASB reactor, the values of μ_m and K_s are 0.00825 per day and 886.6 mg/L, respectively.

5.2 Recommendations

This study has shown that both UASB and HUASB reactors have potential to be used as treatment alternatives for non-penicillin pharmaceutical wastewater. However, the UASB and HUASB reactors require post treatment in treating high strength pharmaceutical wastewater. Moreover, nutrient treatment is required because the nutrient removals were negligible during this study. Combined treatment for organics and nutrients removal, using anaerobic process and other biological process can be

used as an alternative for non-penicillin pharmaceutical wastewater treatment. Response of UASB and HUASB reactors to shock loads from non-penicillin pharmaceutical wastewater may be studied. Further study is required to study the effect of acclimatization period and method on the anaerobic reactor performance.

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APPENDIX A PARAMETER ANALYSIS

A.1 COD data for the UASB and HUASB reactors

Table A.1 Influent and effluent COD concentrations, OLR, and COD removal data in the mesophilic and thermophilic UASB reactors

Date	Days	Influent COD (mg/L)				OLR (g COD/L/.d)	Effluent COD M-UASB (mg/L)				Rem. %	Effluent COD T-UASB (mg/L)				Rem. %
		S1	S2	S3	Ave.		S1	S2	S3	Ave.		S1	S2	S3	Ave.	
Low strength influent; HRT of five days																
30-Nov-07	1	487	504	499	497	0.10	64	64	63	64	87.18	291	296	295	294	40.81
02-Dec-07	3	491	493	496	493	0.10	67	72	68	69	86.01	178	179	187	181	63.24
04-Dec-07	5	513	483	494	497	0.10	73	73	67	71	85.70	168	160	156	161	67.52
06-Dec-07	7	500	501	495	499	0.10	69	62	63	65	87.03	124	117	119	120	75.94
08-Dec-07	9	471	468	469	469	0.09	47	48	48	48	89.84	84	76	80	80	82.95
10-Dec-07	11	462	458	454	458	0.09	43	43	43	43	90.61	77	78	79	78	82.97
12-Dec-07	13	500	496	502	499	0.10	54	60	66	60	87.98	108	97	99	101	79.71
Low strength influent; HRT of three days																
16-Dec-07	17	504	515	518	512	0.17	82	91	87	87	83.08	141	134	131	135	73.58
18-Dec-07	19	503	502	513	506	0.17	63	56	65	61	87.88	116	112	103	110	78.19
20-Dec-07	21	499	491	478	489	0.16	64	52	59	58	88.08	113	120	115	116	76.29
22-Dec-07	23	510	495	489	498	0.17	59	56	62	59	88.15	111	108	110	110	77.98
24-Dec-07	25	494	493	504	497	0.17	71	69	72	71	85.78	129	126	132	129	74.04
26-Dec-07	27	508	498	519	508	0.17	75	80	79	78	84.66	146	136	139	140	72.39
28-Dec-07	29	473	493	498	488	0.16	86	85	81	84	82.79	139	137	129	135	72.34
01-Jan-08	33	490	483	482	485	0.16	108	94	94	99	79.66	146	139	140	142	70.79
03-Jan-08	35	504	503	513	507	0.17	88	89	85	87	82.76	123	131	127	127	74.93
07-Jan-08	39	526	518	518	521	0.17	89	87	77	84	83.80	112	115	111	113	78.36
09-Jan-08	41	515	517	515	516	0.17	76	76	67	73	85.84	95	99	98	97	81.12
11-Jan-08	43	493	499	493	495	0.17	64	65	67	65	86.80	98	99	92	96	80.54
13-Jan-08	45	500	512	498	503	0.17	67	67	65	66	86.82	111	115	117	114	77.28
15-Jan-08	47	478	488	483	483	0.16	68	67	68	68	85.99	91	99	98	96	80.12

Table A.1 (Continued)

Date	Days	Influent COD (mg/L)				OLR (g COD/L/.d)	Effluent COD M-UASB (mg/L)				Rem. %	Effluent COD T-UASB (mg/L)				Rem. %
		S1	S2	S3	Ave.		S1	S2	S3	Ave.		S1	S2	S3	Ave.	
Low strength influent; HRT of three days (continued)																
17-Jan-08	49	487	488	482	486	0.16	52	55	57	55	88.74	95	89	93	92	80.99
21-Jan-08	53	526	520	532	526	0.18	51	46	47	48	90.87	75	67	66	69	86.82
23-Jan-08	55	511	498	493	501	0.17	65	54	55	58	88.42	73	72	68	71	85.82
25-Jan-08	57	503	529	518	517	0.17	59	61	66	62	88.00	71	69	79	73	85.87
27-Jan-08	59	504	514	519	512	0.17	63	65	63	64	87.57	70	86	73	76	85.10
29-Jan-08	61	520	514	512	515	0.17	61	68	62	64	87.65	73	75	81	76	85.19
31-Jan-08	63	520	524	514	519	0.17	43	47	53	48	90.82	79	76	81	79	84.85
02-Feb-08	65	504	531	501	512	0.17	54	47	49	50	90.23	75	65	73	71	86.13
04-Feb-08	67	521	502	505	509	0.17	45	52	54	50	90.12	79	85	82	82	83.90
06-Feb-08	69	506	507	516	510	0.17	49	51	54	51	89.93	66	72	82	73	85.61
10-Feb-08	73	505	512	500	506	0.17	51	51	54	52	89.72	65	68	66	66	86.88
12-Feb-08	75	499	508	501	503	0.17	52	48	61	54	89.32	66	71	75	71	85.94
High strength influent; HRT of five days																
14-Feb-08	77	2110	2160	2150	2140	0.43	75	77	76	76	96.45	106	124	115	115	94.63
16-Feb-08	79	2200	2240	2210	2217	0.44	94	95	97	95	95.70	169	174	165	169	92.36
18-Feb-08	81	2200	2140	2150	2163	0.43	120	124	123	122	94.35	144	155	150	150	93.08
20-Feb-08	83	2150	2130	2130	2137	0.43	133	131	132	132	93.82	199	201	201	200	90.62
22-Feb-08	85	2120	2090	2080	2097	0.42	170	165	169	168	91.99	213	218	215	215	89.73
24-Feb-08	87	2080	1920	1910	1970	0.39	207	205	202	205	89.61	294	303	296	298	84.89
26-Feb-08	89	2080	2170	2120	2123	0.42	239	229	233	234	89.00	252	254	252	253	88.10
01-Mar-08	93	2160	2160	2190	2170	0.43	234	227	230	230	89.39	233	338	344	305	85.94

Table A.1 (Continued)

Date	Days	Influent COD (mg/L)				OLR (g COD/L/d)	Effluent COD M-UASB (mg/L)				Rem. %	Effluent COD T-UASB (mg/L)				Rem. %
		S1	S2	S3	Ave.		S1	S2	S3	Ave.		S1	S2	S3	Ave.	
High strength influent; HRT of four days																
05-Mar-08	97	1980	2060	1990	2010	0.50	319	317	316	317	84.21	385	384	380	383	80.95
09-Mar-08	101	2020	2040	2010	2023	0.51	252	242	249	248	87.76	313	305	305	308	84.79
11-Mar-08	103	2120	2100	2000	2073	0.52	244	259	258	254	87.77	371	362	364	366	82.36
13-Mar-08	105	2010	2000	2070	2027	0.51	223	227	226	225	88.88	324	312	319	318	84.29
15-Mar-08	107	1990	2070	1990	2017	0.50	239	251	248	246	87.80	362	378	372	371	81.62
17-Mar-08	109	2030	1950	1910	1963	0.49	260	253	267	260	86.76	369	376	362	369	81.21
25-Mar-08	117	2010	2020	2000	2010	0.50	1248	1255	1260	1254	37.60	343	341	347	344	82.90
29-Mar-08	121	2050	2040	2020	2037	0.51	816	833	824	824	59.53	386	386	387	386	81.03
02-Apr-08	125	1890	1950	1980	1940	0.49	849	840	841	843	56.53	334	318	330	327	83.13
06-Apr-08	129	2030	2080	2020	2043	0.51	628	629	827	695	66.00	297	313	300	303	85.15
10-Apr-08	133	1880	1910	1910	1900	0.48	549	546	546	547	71.21	274	266	271	270	85.77
14-Apr-08	137	1980	1990	1950	1973	0.49	479	463	571	504	74.44	297	316	310	308	84.41
18-Apr-08	141	1850	1840	1870	1853	0.46	350	358	352	353	80.94	248	231	232	237	87.21
22-Apr-08	145	1990	2010	1940	1980	0.50	245	267	350	287	85.49	313	317	320	317	84.01
High strength influent; HRT of three days																
27-Apr-08	150	1960	1990	1980	1977	0.66	393	309	603	435	77.99	333	330	331	331	83.24
29-Apr-08	152	1970	1960	1950	1960	0.65	542	556	543	547	72.09	363	368	365	365	81.36
01-May-08	154	1950	1930	1920	1933	0.64	495	501	494	497	74.31	328	332	335	332	82.84
05-May-08	158	1830	1850	1830	1837	0.61	385	381	384	383	79.13	280	281	285	282	84.65
07-May-08	160	1780	1880	1860	1840	0.61	402	391	390	394	78.57	331	330	321	327	82.21

Table A.1 (Continued)

Date	Days	Influent COD (mg/L)				OLR (g COD/L/.d)	Effluent COD M-UASB (mg/L)				Rem. %	Effluent COD T-UASB (mg/L)				Rem. %
		S1	S2	S3	Ave.		S1	S2	S3	Ave.		S1	S2	S3	Ave.	
High strength influent; HRT of three days (continued)																
09-May-08	162	1810	1760	1750	1773	0.59	359	363	363	362	79.61	428	412	415	418	76.41
11-May-08	164	1830	1860	1870	1853	0.62	338	339	339	339	81.73	412	420	418	417	77.52
13-May-08	166	1900	1910	1870	1893	0.63	342	356	350	349	81.55	488	500	480	489	74.15
15-May-08	168	1860	1890	1870	1873	0.62	388	394	390	391	79.15	490	487	483	487	74.02
17-May-08	170	1830	1860	1910	1867	0.62	348	345	346	346	81.45	477	487	478	481	74.25
20-May-08	173	1850	1890	1880	1873	0.62	356	370	366	364	80.57	468	466	479	471	74.86
22-May-08	175	1820	1830	1830	1827	0.61	374	382	388	381	79.12	465	466	468	466	74.47
24-May-08	177	1880	1850	1860	1863	0.62	380	372	365	372	80.02	480	478	477	478	74.33
26-May-08	179	1870	1860	1890	1873	0.62	380	378	376	378	79.82	466	461	468	465	75.18
High strength influent; HRT of two days																
28-May-08	181	1830	1880	1850	1853	0.93	560	551	549	553	70.14	590	610	609	603	67.46
30-May-08	183	1790	1820	1840	1817	0.91	530	523	511	521	71.30	710	717	728	718	60.46
01-Jun-08	185	1830	1840	1850	1840	0.92	521	532	525	526	71.41	722	732	725	726	60.53
03-Jun-08	187	1780	1790	1810	1793	0.90	490	488	479	486	72.92	680	669	673	674	62.42
05-Jun-08	189	1810	1850	1870	1843	0.92	477	478	489	481	73.89	640	631	632	634	65.59
07-Jun-08	191	1890	1870	1870	1877	0.94	461	463	468	464	75.28	621	618	616	618	67.05
09-Jun-08	193	1840	1800	1810	1817	0.91	460	473	466	466	74.33	580	588	578	582	67.96
11-Jun-08	195	1780	1820	1850	1817	0.91	423	431	428	427	76.48	560	555	551	555	69.43
13-Jun-08	197	1790	1780	1760	1777	0.89	431	420	422	424	76.12	539	553	554	549	69.12
15-Jun-08	199	1780	1770	1760	1770	0.89	421	427	428	425	75.97	552	554	553	553	68.76

Table A.2 Influent and effluent COD concentrations, OLR, and COD removal data in the mesophilic and thermophilic HUASB reactors

Date	Days	Influent COD (mg/L)				OLR (g COD/L/.d)	Effluent COD M-HUASB (mg/L)				Rem. %	Effluent COD T-HUASB (mg/L)				Rem. %
		S1	S2	S3	Ave.		S1	S2	S3	Ave.		S1	S2	S3	Ave.	
Low strength influent; HRT of three days																
31-Jan-08	63	520	524	514	519	0.17	78	78	76	77	85.11	285	280	278	281	45.89
02-Feb-08	65	504	531	501	512	0.17	87	81	85	84	83.53	232	230	226	229	55.21
04-Feb-08	67	521	502	505	509	0.17	66	70	68	68	86.65	188	189	192	190	62.76
06-Feb-08	69	506	507	516	510	0.17	49	49	51	50	90.26	157	160	159	159	68.87
10-Feb-08	73	505	512	500	506	0.17	39	43	42	41	91.83	182	175	178	178	64.73
12-Feb-08	75	499	508	501	503	0.17	45	44	40	43	91.45	168	159	162	163	67.57
High strength influent; HRT of five days																
14-Feb-08	77	2110	2160	2150	2140	0.43	116	126	124	122	94.30	251	251	254	252	88.22
16-Feb-08	79	2200	2240	2210	2217	0.44	109	118	115	114	94.86	266	252	160	226	89.80
18-Feb-08	81	2200	2140	2150	2163	0.43	130	122	125	126	94.19	273	273	274	273	87.37
20-Feb-08	83	2150	2130	2130	2137	0.43	128	126	120	125	94.17	300	302	299	300	85.94
22-Feb-08	85	2120	2090	2080	2097	0.42	145	146	152	148	92.96	311	314	316	314	85.04
24-Feb-08	87	2080	1920	1910	1970	0.39	131	135	134	133	93.23	298	302	303	301	84.72
26-Feb-08	89	2080	2170	2120	2123	0.42	139	130	139	136	93.59	296	294	294	295	86.12
01-Mar-08	93	2160	2160	2190	2170	0.43	163	153	157	158	92.73	288	279	283	283	86.94
High strength influent; HRT of four days																
05-Mar-08	97	1980	2060	1990	2010	0.50	193	194	192	193	90.40	558	558	552	556	72.34
09-Mar-08	101	2020	2040	2010	2023	0.51	174	176	180	177	91.27	561	557	541	553	72.67
11-Mar-08	103	2120	2100	2000	2073	0.52	244	251	247	247	88.07	423	421	417	420	79.73
13-Mar-08	105	2010	2000	2070	2027	0.51	209	208	209	209	89.70	417	417	412	415	79.51
15-Mar-08	107	1990	2070	1990	2017	0.50	180	187	182	183	90.93	422	411	421	418	79.27
17-Mar-08	109	2030	1950	1910	1963	0.49	198	196	199	198	89.93	412	410	414	412	79.02
25-Mar-08	117	2010	2020	2000	2010	0.50	221	214	228	221	89.00	400	399	422	407	79.75
29-Mar-08	121	2050	2040	2020	2037	0.51	233	232	231	232	88.61	330	335	344	336	83.49
02-Apr-08	125	1890	1950	1980	1940	0.49	197	194	195	195	89.93	308	310	317	312	83.93
06-Apr-08	129	2030	2080	2020	2043	0.51	227	221	226	225	89.00	342	348	350	347	83.03
10-Apr-08	133	1880	1910	1910	1900	0.48	181	187	183	184	90.33	307	305	301	304	83.98
14-Apr-08	137	1980	1990	1950	1973	0.49	195	185	191	190	90.35	329	320	319	323	83.65

Table A.2 (Continued)

Date	Days	Influent COD (mg/L)				OLR (g COD/L/.d)	Effluent COD M-HUASB (mg/L)				Rem. %	Effluent COD T-HUASB (mg/L)				Rem. %
		S1	S2	S3	Ave.		S1	S2	S3	Ave.		S1	S2	S3	Ave.	
High strength influent; HRT of four days (continued)																
18-Apr-08	141	1850	1840	1870	1853	0.46	227	224	225	225	87.84	351	350	344	348	81.21
22-Apr-08	145	1990	2010	1940	1980	0.50	230	231	225	229	88.45	344	351	355	350	82.32
High strength influent; HRT of three days																
27-Apr-08	150	1960	1990	1980	1977	0.66	260	254	255	256	87.03	568	577	578	574	70.94
29-Apr-08	152	1970	1960	1950	1960	0.65	253	269	256	259	86.77	592	593	589	591	69.83
01-May-08	154	1950	1930	1920	1933	0.64	237	235	230	234	87.90	479	475	474	476	75.38
05-May-08	158	1830	1850	1830	1837	0.61	251	233	240	241	86.86	350	349	347	349	81.02
07-May-08	160	1780	1880	1860	1840	0.61	270	268	265	268	85.45	326	320	316	321	82.57
09-May-08	162	1810	1760	1750	1773	0.59	257	245	246	249	85.94	347	348	347	347	80.41
11-May-08	164	1830	1860	1870	1853	0.62	263	276	271	270	85.43	374	375	379	376	79.71
13-May-08	166	1900	1910	1870	1893	0.63	290	279	282	284	85.02	307	305	302	305	83.91
15-May-08	168	1860	1890	1870	1873	0.62	288	279	283	283	84.88	404	410	415	410	78.13
17-May-08	170	1830	1860	1910	1867	0.62	305	307	299	304	83.73	408	410	410	409	78.07
20-May-08	173	1850	1890	1880	1873	0.62	310	302	301	304	83.75	380	389	388	386	79.41
22-May-08	175	1820	1830	1830	1827	0.61	281	276	288	282	84.58	431	421	423	425	76.73
24-May-08	177	1880	1850	1860	1863	0.62	282	282	276	280	84.97	390	395	388	391	79.02
26-May-08	179	1870	1860	1890	1873	0.62	271	268	265	268	85.69	383	380	391	385	79.47
High strength influent; HRT of two days																
28-May-08	181	1830	1880	1850	1853	0.93	288	281	285	285	84.64	550	554	531	545	70.59
30-May-08	183	1790	1820	1840	1817	0.91	290	299	297	295	83.74	481	470	476	476	73.82
01-Jun-08	185	1830	1840	1850	1840	0.92	310	318	314	314	82.93	489	480	491	487	73.55
03-Jun-08	187	1780	1790	1810	1793	0.90	321	319	312	317	82.30	521	498	512	510	71.54
05-Jun-08	189	1810	1850	1870	1843	0.92	361	356	355	357	80.61	470	461	455	462	74.94
07-Jun-08	191	1890	1870	1870	1877	0.94	364	374	376	371	80.21	488	478	493	486	74.09
09-Jun-08	193	1840	1800	1810	1817	0.91	310	318	309	312	82.81	453	444	435	444	75.56
11-Jun-08	195	1780	1820	1850	1817	0.91	308	301	296	302	83.39	437	431	427	432	76.24
13-Jun-08	197	1790	1780	1760	1777	0.89	326	313	320	320	82.01	441	432	435	436	75.46
15-Jun-08	199	1780	1770	1760	1770	0.89	312	314	310	312	82.37	447	455	441	448	74.71

Table A.3 Influent and effluent BOD₅ concentrations and BOD₅ removal data in the mesophilic and thermophilic UASB reactors

Date	Days	Influent BOD ₅ (mg/L)				Effluent BOD ₅ M-UASB (mg/L)				Rem. %	Effluent BOD ₅ T-UASB (mg/L)				Rem. %
		S1	S2	S3	Ave.	S1	S2	S3	Ave.		S1	S2	S3	Ave.	
Low strength influent; HRT of five days															
04-Dec-07	5	305	310	318	311	23	25	26	25	92	34	35	37	35	89
08-Dec-07	9	310	307	279	299	18	21	21	20	93	33	31	30	31	90
12-Dec-07	13	315	296	301	304	33	45	31	36	88	34	43	40	39	87
Low strength influent; HRT of three days															
16-Dec-07	17	319	300	299	306	47	53	46	49	84	55	54	51	53	83
20-Dec-07	21	318	316	312	315	33	25	27	28	91	44	46	38	43	86
22-Dec-07	23	305	305	304	305	22	20	20	21	93	36	30	33	33	89
26-Dec-07	27	330	323	341	331	32	24	22	26	92	33	30	38	34	90
01-Jan-08	33	364	359	361	361	24	25	28	26	93	40	39	38	39	89
09-Jan-08	41	402	374	383	386	29	27	25	27	93	32	35	38	35	91
13-Jan-08	45	370	366	358	365	35	33	28	32	91	44	41	39	41	89
15-Jan-08	47	324	367	349	347	36	31	25	31	91	51	41	45	46	87
21-Jan-08	53	357	355	346	353	34	38	31	34	90	43	48	41	44	88
23-Jan-08	55	362	348	345	352	41	34	31	35	90	35	31	27	31	91
27-Jan-08	59	321	343	336	333	27	28	24	26	92	27	35	31	31	91
29-Jan-08	61	310	327	316	318	34	40	34	36	89	28	31	38	32	90
02-Feb-08	65	318	323	344	328	34	24	25	28	92	34	30	41	35	89
04-Feb-08	67	319	322	334	325	16	20	22	19	94	24	28	24	25	92
06-Feb-08	69	377	383	384	381	13	16	14	14	96	18	24	30	24	94
10-Feb-08	73	388	383	367	379	25	22	16	21	94	34	27	33	31	92
12-Feb-08	75	374	396	380	383	21	17	22	20	95	24	29	31	28	93
High strength influent; HRT of five days															
16-Feb-08	79	1581	1632	1588	1600	43	40	42	42	97	72	77	81	77	95
20-Feb-08	83	1512	1561	1604	1559	80	67	55	68	96	132	123	111	122	92
24-Feb-08	87	1405	1435	1440	1427	72	90	73	78	95	166	164	148	159	89
26-Feb-08	89	1450	1514	1534	1499	88	71	77	79	95	144	148	152	148	90
01-Mar-08	93	1525	1612	1590	1576	75	73	63	70	96	136	172	179	163	90

Table A.3 (Continued)

Date	Days	Influent BOD ₅ (mg/L)				Effluent BOD ₅ M-UASB (mg/L)				Rem. %	Effluent BOD ₅ T-UASB (mg/L)				Rem. %
		S1	S2	S3	Ave.	S1	S2	S3	Ave.		S1	S2	S3	Ave.	
High strength influent; HRT of four days															
05-Mar-08	97	1497	1513	1523	1511	122	134	131	129	91	213	207	204	208	86
09-Mar-08	101	1454	1489	1487	1477	146	140	147	144	90	221	225	213	220	85
13-Mar-08	105	1487	1560	1573	1540	112	107	102	107	93	214	159	169	181	88
17-Mar-08	109	1482	1463	1394	1446	133	119	112	121	92	251	241	192	228	84
29-Mar-08	121	1415	1428	1394	1412	392	383	371	382	73	220	224	197	214	85
06-Apr-08	129	1360	1414	1394	1389	295	315	380	330	76	172	185	183	180	87
14-Apr-08	137	1366	1433	1365	1388	216	181	240	212	85	175	180	158	171	88
18-Apr-08	141	1401	1388	1397	1395	123	128	118	123	91	188	178	167	178	87
22-Apr-08	145	1401	1456	1366	1408	105	109	137	117	92	191	197	208	198	86
High strength influent; HRT of three days															
29-Apr-08	152	1438	1490	1521	1483	189	201	213	201	86	195	202	234	210	86
01-May-08	154	1367	1388	1371	1375	185	181	177	181	87	222	218	211	217	84
05-May-08	158	1409	1459	1425	1431	185	171	157	171	88	248	252	260	253	82
09-May-08	162	1385	1367	1348	1367	176	171	163	170	88	257	251	245	251	82
13-May-08	166	1344	1365	1351	1353	171	181	183	178	87	268	256	267	264	81
15-May-08	168	1336	1318	1321	1325	198	173	187	186	86	274	248	251	258	81
17-May-08	170	1208	1283	1280	1257	181	183	166	177	86	281	302	277	287	77
20-May-08	173	1184	1247	1203	1212	153	167	187	169	86	285	247	235	256	79
24-May-08	177	1222	1277	1246	1248	160	190	183	177	86	272	263	267	267	79
High strength influent; HRT of two days															
28-May-08	181	1281	1272	1288	1280	252	242	236	244	81	330	311	292	311	76
01-Jun-08	185	1186	1211	1199	1198	301	288	280	290	76	314	300	326	313	74
05-Jun-08	189	1231	1314	1290	1278	196	182	201	193	85	283	299	278	287	78
09-Jun-08	193	1270	1260	1285	1272	212	208	200	207	84	319	300	283	301	76
13-Jun-08	197	1243	1223	1255	1240	211	185	190	195	84	329	304	310	314	75
15-Jun-08	199	1264	1186	1162	1204	177	195	183	185	85	298	283	299	293	76

Table A.4 Influent and effluent BOD₅ concentrations and BOD₅ removal data in the mesophilic and thermophilic HUASB reactors

Date	Days	Influent BOD ₅ (mg/L)				Effluent BOD ₅ M-HUASB (mg/L)				Rem. %	Effluent BOD ₅ T-HUASB (mg/L)				Rem. %
		S1	S2	S3	Ave.	S1	S2	S3	Ave.		S1	S2	S3	Ave.	
Low strength influent; HRT of three days															
04-Feb-08	67	319	322	334	325	29	37	32	33	90	101	98	92	97	70
06-Feb-08	69	377	383	384	381	34	38	31	34	91	83	78	81	81	79
10-Feb-08	73	388	383	367	379	18	22	20	20	95	78	85	72	78	79
12-Feb-08	75	374	396	380	383	23	21	18	21	95	87	72	73	77	80
High strength influent; HRT of five days															
16-Feb-08	79	1581	1632	1588	1600	40	44	36	40	97	179	170	164	171	89
20-Feb-08	83	1512	1561	1604	1559	47	41	39	42	97	167	159	161	162	90
24-Feb-08	87	1405	1435	1440	1427	55	51	47	51	96	148	143	142	144	90
26-Feb-08	89	1450	1514	1534	1499	58	45	51	51	97	135	147	131	138	91
01-Mar-08	93	1525	1612	1590	1576	78	69	66	71	95	142	141	136	140	91
High strength influent; HRT of four days															
05-Mar-08	97	1497	1513	1523	1511	99	96	87	94	94	271	266	263	267	82
09-Mar-08	101	1454	1489	1487	1477	85	79	77	81	95	264	256	238	253	83
13-Mar-08	105	1487	1560	1573	1540	98	106	94	99	94	204	183	173	187	88
17-Mar-08	109	1482	1463	1394	1446	89	88	92	90	94	202	209	215	209	86
29-Mar-08	121	1415	1428	1394	1412	119	125	116	120	92	149	147	182	159	89
06-Apr-08	129	1360	1414	1394	1389	116	104	115	112	92	150	164	179	164	88
14-Apr-08	137	1366	1433	1365	1388	94	87	82	88	94	125	131	118	125	91
18-Apr-08	141	1401	1388	1397	1395	84	88	91	88	94	123	127	119	123	91
22-Apr-08	145	1401	1456	1366	1408	99	88	83	90	94	110	144	124	126	91

Table A.4 (Continued)

Date	Days	Influent BOD ₅ (mg/L)				Effluent BOD ₅ M-HUASB (mg/L)				Rem. %	Effluent BOD ₅ T-HUASB (mg/L)				Rem. %
		S1	S2	S3	Ave.	S1	S2	S3	Ave.		S1	S2	S3	Ave.	
High strength influent; HRT of three days															
29-Apr-08	152	1438	1490	1521	1483	104	89	115	103	93	198	196	206	200	87
01-May-08	154	1367	1388	1371	1375	88	97	107	97	93	166	161	151	159	88
05-May-08	158	1409	1459	1425	1431	120	100	96	106	93	133	141	121	132	91
09-May-08	162	1385	1367	1348	1367	121	103	111	111	92	125	138	144	136	90
13-May-08	166	1344	1365	1351	1353	109	111	105	108	92	135	134	143	137	90
15-May-08	168	1336	1318	1321	1325	127	114	108	116	91	141	185	158	161	88
17-May-08	170	1208	1283	1280	1257	137	135	120	131	90	135	168	144	149	88
20-May-08	173	1184	1247	1203	1212	130	136	123	130	89	163	171	159	165	86
24-May-08	177	1222	1277	1246	1248	135	133	135	134	89	172	174	175	173	86
High strength influent; HRT of two days															
28-May-08	181	1281	1272	1288	1280	141	124	120	128	90	275	294	260	276	78
01-Jun-08	185	1186	1211	1199	1198	163	146	160	156	87	233	226	236	231	81
05-Jun-08	189	1231	1314	1290	1278	146	117	124	129	90	185	193	209	196	85
09-Jun-08	193	1270	1260	1285	1272	118	95	108	107	92	199	204	178	194	85
13-Jun-08	197	1243	1223	1255	1240	108	100	99	102	92	216	194	200	204	84
15-Jun-08	199	1264	1186	1162	1204	115	100	112	109	91	215	214	185	205	83

Table A.5 Influent and effluent NH₃-N concentrations data in the UASB and HUASB reactors

Date	Days	Influent NH ₃ -N (mg/L)				Effluent NH ₃ -N M-UASB (mg/L)				Effluent NH ₃ -N T-UASB (mg/L)				Effluent NH ₃ -N M-HUASB (mg/L)				Effluent NH ₃ -N T-HUASB (mg/L)			
		S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave
Low strength influent; HRT of five days																					
02-Dec-07	3	3.4	2.6	3.5	3.2	12.8	12.5	13.8	13.0	17.6	11.7	11.9	13.7								
04-Dec-07	5	2.4	3.3	3.2	3.0	12.7	12.5	12.8	12.7	12.3	12.6	12.5	12.5								
08-Dec-07	9	3.7	2.5	3.2	3.1	12.2	11.9	12.0	12.0	11.4	11.5	11.6	11.5								
10-Dec-07	11	3.5	3.4	3.0	3.3	12.8	13.2	13.1	13.0	11.9	12.1	11.8	11.9								
12-Dec-07	13	3.6	3.7	3.8	3.7	11.5	11.2	11.8	11.5	8.5	8.7	8.3	8.5								
Low strength influent; HRT of three days																					
16-Dec-07	17	3.8	4.4	4.0	4.1	4.6	4.5	4.5	4.5	4.2	4.1	4.1	4.1								
18-Dec-07	19	2.4	2.5	2.5	2.5	5.9	6.2	6.1	6.1	5.8	4.9	5.6	5.4								
20-Dec-07	21	2.7	3.1	3.0	2.9	6.7	6.4	6.3	6.5	5.0	5.6	5.3	5.3								
22-Dec-07	23	2.6	3.6	3.0	3.1	6.6	7.4	6.2	6.7	3.6	4.2	3.9	3.9								
24-Dec-07	25	6.3	5.5	5.8	5.9	9.3	10.5	11.8	10.5	7.5	6.8	6.6	7.0								
26-Dec-07	27	5.4	5.1	6.3	5.6	10.3	9.8	10.2	10.1	8.5	8.7	8.4	8.5								
28-Dec-07	29	6.0	5.9	6.0	6.0	9.6	12.6	10.2	10.8	9.4	10.2	9.7	9.8								
01-Jan-08	33	4.3	4.0	4.8	4.4	9.9	10.3	10.7	10.3	6.3	6.8	6.9	6.7								
03-Jan-08	35	4.8	4.6	4.4	4.6	10.0	10.5	10.8	10.4	7.5	7.8	7.7	7.7								
07-Jan-08	39	4.9	5.5	4.7	5.0	9.6	9.9	9.1	9.5	6.5	6.9	7.2	6.9								
09-Jan-08	41	5.1	5.0	4.8	5.0	9.0	8.5	8.2	8.6	6.6	6.3	7.0	6.6								
11-Jan-08	43	5.5	5.2	5.1	5.3	8.8	8.7	8.5	8.7	8.8	8.1	8.2	8.4								
13-Jan-08	45	4.8	4.8	5.1	4.9	8.9	8.8	9.4	9.0	7.6	7.4	7.7	7.6								
15-Jan-08	47	4.5	4.6	4.8	4.6	7.8	8.1	8.5	8.1	7.5	8.2	7.7	7.8								
17-Jan-08	49	4.7	4.6	4.4	4.6	8.5	9.3	8.8	8.9	7.9	8.5	8.7	8.4								
21-Jan-08	53	4.9	5.1	5.2	5.1	8.7	8.9	8.4	8.7	8.5	8.1	8.7	8.4								
23-Jan-08	55	4.4	4.7	4.5	4.5	9.1	9.3	9.8	9.4	7.4	7.5	7.3	7.4								
27-Jan-08	59	4.5	4.5	4.6	4.5	9.2	8.8	8.9	9.0	7.7	7.5	7.6	7.6								

Table A.5 (Continued)

Date	Days	Influent NH ₃ -N (mg/L)				Effluent NH ₃ -N M-UASB (mg/L)				Effluent NH ₃ -N T-UASB (mg/L)				Effluent NH ₃ -N M-HUASB (mg/L)				Effluent NH ₃ -N T-HUASB (mg/L)			
		S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave
Low strength influent; HRT of three days (continued)																					
31-Jan-08	63	5.1	5.3	5.0	5.1	8.7	8.8	8.6	8.7	7.9	7.3	7.5	7.6	18.9	19.0	18.9	18.9	13.2	13.6	13.5	13.4
04-Feb-08	67	4.4	4.7	4.8	4.6	8.9	8.3	8.9	8.7	7.4	8.1	7.3	7.6	19.0	18.2	19.4	18.9	14.4	13.8	14.2	14.1
10-Feb-08	73	4.9	4.8	4.6	4.8	8.8	8.4	9.1	8.8	7.7	7.8	7.9	7.8	19.5	19.3	19.4	19.4	13.7	13.6	14.0	13.8
12-Feb-08	75	4.6	4.8	5.0	4.8	9.1	9.2	8.8	9.0	8.1	7.9	7.7	7.9	18.7	18.1	18.5	18.4	13.5	14.3	14.0	13.9
High strength influent; HRT of five days																					
14-Feb-08	77	12.4	13.2	12.3	12.6	20.3	20.2	20.2	20.2	9.3	8.3	8.9	8.8	13.9	13.7	13.6	13.7	11.6	11.5	11.4	11.5
16-Feb-08	79	11.9	12.3	11.5	11.9	19.1	18.9	18.7	18.9	10.5	11.0	11.3	10.9	15.0	14.0	14.6	14.5	13.9	13.7	13.8	13.8
20-Feb-08	83	13.3	13.4	13.6	13.4	19.9	20.0	20.0	20.0	13.9	14.2	14.3	14.1	13.7	14.5	14.2	14.1	16.2	17.0	16.1	16.4
24-Feb-08	87	16.0	16.4	16.3	16.2	18.9	19.7	18.8	19.1	15.2	16.0	15.7	15.6	15.6	15.3	14.9	15.3	16.0	15.7	15.3	15.7
01-Mar-08	93	19.6	19.4	18.9	19.3	17.7	17.5	18.0	17.7	14.2	13.9	13.5	13.9	18.7	19.5	18.6	18.9	16.7	15.7	16.3	16.2
High strength influent; HRT of four days																					
09-Mar-08	101	16.3	16.1	16.2	16.2	15.4	15.2	15.3	15.3	11.9	12.0	12.2	12.0	16.5	16.3	15.8	16.2	15.7	15.6	15.8	15.7
13-Mar-08	105	16.2	16.0	16.3	16.2	16.3	16.2	16.6	16.4	14.0	13.9	13.9	13.9	17.8	18.4	17.8	18.0	18.0	17.1	17.2	17.4
17-Mar-08	109	15.2	15.7	16.0	15.6	17.5	17.5	17.2	17.4	13.8	13.3	13.0	13.4	17.5	16.9	17.7	17.4	15.1	16.3	15.6	15.7
29-Mar-08	121	15.0	14.4	14.8	14.7	14.8	14.7	14.6	14.7	12.9	12.3	13.1	12.8	18.6	18.4	18.2	18.4	16.3	16.1	16.0	16.1
06-Apr-08	129	14.6	14.4	14.2	14.4	13.3	13.7	13.6	13.5	11.8	11.7	11.9	11.8	19.1	19.0	19.2	19.1	14.1	14.2	14.4	14.2
14-Apr-08	137	14.4	14.3	14.3	14.3	12.9	12.6	12.6	12.7	13.7	13.8	14.0	13.8	18.6	18.5	18.9	18.7	14.3	13.5	14.0	13.9
22-Apr-08	145	12.5	13.1	12.5	12.7	15.9	15.7	15.2	15.6	12.9	12.7	13.2	12.9	18.6	18.5	18.4	18.5	13.8	14.1	13.5	13.8
High strength influent; HRT of three days																					
29-Apr-08	152	12.6	12.7	12.1	12.5	13.5	14.0	14.3	14.0	13.7	13.5	13.0	13.4	17.8	17.9	18.1	17.9	12.7	12.8	13.2	12.9
05-May-08	158	12.1	12.4	12.5	12.3	14.2	14.5	14.6	14.4	13.5	13.9	13.8	13.7	17.8	17.8	17.7	17.8	13.5	13.3	13.6	13.5
09-May-08	162	11.3	11.7	11.0	11.3	14.9	14.7	14.8	14.8	13.7	13.8	14.0	13.8	17.5	17.9	17.8	17.7	13.8	13.4	13.0	13.4
15-May-08	168	12.4	11.5	11.6	11.8	15.5	16.3	16.0	15.9	13.6	13.8	14.0	13.8	16.7	16.8	17.0	16.8	13.9	14.3	13.5	13.9
17-May-08	170	11.8	11.5	11.5	11.6	16.7	16.4	17.2	16.8	13.2	13.8	13.2	13.4	17.5	16.6	16.7	16.9	14.3	14.0	14.0	14.1
20-May-08	173	12.6	12.9	12.3	12.6	15.7	15.6	15.4	15.6	14.1	13.3	13.8	13.7	17.3	17.4	16.8	17.2	14.1	13.8	14.6	14.2
24-May-08	177	12.7	12.8	12.8	12.8	16.2	15.8	15.4	15.8	13.8	14.2	13.4	13.8	17.1	17.4	17.5	17.3	14.7	14.6	14.6	14.6
26-May-08	179	11.7	11.5	12.0	11.7	16.0	16.1	16.5	16.2	14.2	13.9	13.9	14.0	16.9	17.2	17.3	17.1	14.7	14.8	14.8	14.8

Table A.5 (Continued)

Date	Days	Influent NH ₃ -N (mg/L)				Effluent NH ₃ -N M-UASB (mg/L)				Effluent NH ₃ -N T-UASB (mg/L)				Effluent NH ₃ -N M-HUASB (mg/L)				Effluent NH ₃ -N T-HUASB (mg/L)			
		S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave
High strength influent; HRT of two days																					
28-May-08	181	12.7	12.5	12.6	12.6	15.8	15.9	16.1	15.9	14.5	14.2	15.0	14.6	17.5	18.0	18.3	17.9	14.7	14.9	15.1	14.9
30-May-08	183	11.5	11.4	11.8	11.6	15.3	14.5	15.7	15.2	13.9	14.0	14.4	14.1	17.9	17.1	17.6	17.5	15.0	14.8	14.3	14.7
01-Jun-08	185	11.1	11.2	11.4	11.2	15.2	14.7	14.4	14.8	13.3	13.4	13.6	13.4	17.3	17.0	17.0	17.1	13.9	14.0	13.4	13.8
05-Jun-08	189	10.9	11.2	11.3	11.1	13.8	13.9	14.1	13.9	13.9	13.8	13.6	13.8	16.4	16.2	16.7	16.4	14.0	13.8	13.9	13.9
07-Jun-08	191	11.8	11.8	11.5	11.7	14.4	15.0	14.4	14.6	14.3	13.9	13.5	13.9	16.1	15.8	16.6	16.2	12.7	12.8	13.0	12.8
09-Jun-08	193	11.7	11.4	11.3	11.5	14.6	14.0	14.8	14.5	13.6	13.7	13.7	13.7	16.3	16.4	16.6	16.4	13.1	13.4	13.5	13.3
11-Jun-08	195	11.3	10.5	11.0	10.9	15.0	14.7	14.6	14.8	12.7	13.9	13.2	13.3	16.2	16.1	15.9	16.1	13.6	12.8	14.0	13.5
13-Jun-08	197	10.0	11.2	10.5	10.6	15.0	15.1	15.3	15.1	13.4	13.2	13.3	13.3	16.0	15.9	15.9	15.9	13.8	14.3	14.6	14.2
15-Jun-08	199	10.6	10.7	11.1	10.8	15.4	15.2	15.1	15.2	13.3	13.6	13.0	13.3	15.6	15.7	15.7	15.7	14.5	14.3	14.8	14.5

Table A.6 Influent and effluent NO₃-N concentrations data in the UASB and HUASB reactors

Date	Days	Influent NO ₃ -N (mg/L)				Effluent NO ₃ -N M-UASB (mg/L)				Effluent NO ₃ -N T-UASB (mg/L)				Effluent NO ₃ -N M-HUASB (mg/L)				Effluent NO ₃ -N T-HUASB (mg/L)			
		S1	S2	S3	Ave	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.
Low strength influent; HRT of five days																					
02-Dec-07	3	0.8	0.7	0.9	0.8	0.6	0.7	0.6	0.6	0.4	0.2	0.5	0.4								
04-Dec-07	5	0.7	0.7	0.5	0.6	0.5	0.6	0.6	0.6	0.3	0.3	0.3	0.3								
08-Dec-07	9	0.7	0.4	1.0	0.7	0.9	0.6	0.7	0.7	0.3	0.3	0.3	0.3								
10-Dec-07	11	0.5	0.7	0.6	0.6	0.3	0.5	0.4	0.4	0.1	0.1	0.2	0.1								
12-Dec-07	13	0.7	0.8	1.1	0.9	0.6	0.7	0.4	0.6	0.2	0.1	0.3	0.2								
Low strength influent; HRT of three days																					
16-Dec-07	17	0.3	0.4	0.2	0.3	0.4	0.5	0.4	0.4	0.5	0.5	0.5	0.5								
18-Dec-07	19	0.4	0.2	0.3	0.3	0.2	0.2	0.1	0.2	0.3	0.6	0.5	0.5								
20-Dec-07	21	0.5	0.5	0.7	0.6	0.5	0.4	0.5	0.5	0.4	0.4	0.4	0.4								
22-Dec-07	23	0.8	0.8	0.7	0.8	0.6	0.7	0.7	0.7	0.9	1.1	1.0	1.0								
24-Dec-07	25	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.7	1.0	1.0	0.8	0.9								
26-Dec-07	27	0.8	0.9	0.9	0.9	0.7	0.7	0.9	0.8	0.9	0.8	0.8	0.8								
28-Dec-07	29	0.7	0.9	0.9	0.8	1.0	0.7	1.0	0.9	1.0	0.9	1.1	1.0								
01-Jan-08	33	1.2	0.9	1.2	1.1	1.2	1.0	1.0	1.1	0.9	0.9	1.0	0.9								
03-Jan-08	35	0.6	0.7	0.6	0.6	0.4	0.5	0.6	0.5	1.1	1.3	1.0	1.1								
07-Jan-08	39	0.5	0.6	0.6	0.6	0.6	0.3	0.5	0.5	0.6	0.7	0.7	0.7								
09-Jan-08	41	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.8	0.6	0.5	0.6								
11-Jan-08	43	0.6	0.6	0.4	0.5	0.4	0.5	0.3	0.4	0.7	0.8	0.7	0.7								
13-Jan-08	45	0.3	0.3	0.4	0.3	0.1	0.1	0.2	0.1	0.3	0.4	0.5	0.4								
15-Jan-08	47	0.4	0.5	0.3	0.4	0.1	0.1	0.3	0.2	0.4	0.4	0.6	0.5								
17-Jan-08	49	0.4	0.4	0.4	0.4	0.2	0.1	0.2	0.2	0.5	0.3	0.3	0.4								
21-Jan-08	53	0.3	0.4	0.4	0.4	0.1	0.3	0.1	0.2	0.4	0.5	0.5	0.5								
23-Jan-08	55	0.5	0.5	0.4	0.5	0.0	0.1	0.1	0.1	0.3	0.4	0.7	0.5								
27-Jan-08	59	0.3	0.4	0.5	0.4	0.2	0.1	0.2	0.2	0.3	0.3	0.4	0.3								

Table A.6 (Continued)

Date	Days	Influent NO ₃ -N (mg/L)				Effluent NO ₃ -N M-UASB (mg/L)				Effluent NO ₃ -N T-UASB (mg/L)				Effluent NO ₃ -N M-HUASB (mg/L)				Effluent NO ₃ -N T-HUASB (mg/L)			
		S1	S2	S3	Ave	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.
Low strength influent; HRT of three days (continued)																					
31-Jan-08	63	0.4	0.4	0.5	0.4	0.1	0.2	0.1	0.1	0.4	0.4	0.4	0.4	0.4	0.2	0.0	0.2	0.3	0.2	0.3	0.3
04-Feb-08	67	0.5	0.4	0.5	0.5	0.3	0.2	0.3	0.3	0.4	0.3	0.4	0.4	0.2	0.3	0.1	0.2	0.2	0.3	0.3	0.3
10-Feb-08	73	0.5	0.5	0.4	0.5	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.2	0.4	0.2
12-Feb-08	75	0.3	0.4	0.4	0.4	0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.3	0.3
High strength influent; HRT of five days																					
14-Feb-08	77	0.4	0.6	0.8	0.6	0.7	0.6	0.5	0.6	0.5	0.6	0.4	0.5	0.1	0.5	0.4	0.3	0.4	0.4	0.1	0.3
16-Feb-08	79	0.5	0.6	0.6	0.6	0.4	0.5	0.5	0.5	0.3	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.1	0.4	0.3
20-Feb-08	83	0.4	0.8	0.7	0.6	0.5	0.4	0.5	0.5	0.4	0.3	0.5	0.4	0.4	0.2	0.3	0.3	0.3	0.2	0.0	0.2
24-Feb-08	87	0.7	0.8	0.6	0.7	0.4	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.1	0.2	0.4	0.2	0.4	0.1	0.1	0.2
01-Mar-08	93	0.4	0.3	0.1	0.3	0.6	0.6	0.7	0.6	0.2	0.1	0.5	0.3	0.3	0.2	0.1	0.2	0.0	0.3	0.4	0.2
High strength influent; HRT of four days																					
09-Mar-08	101	0.5	0.4	0.3	0.4	0.5	0.3	0.2	0.3	0.2	0.4	0.4	0.3	0.5	0.6	0.4	0.5	0.4	0.7	0.8	0.6
13-Mar-08	105	0.5	0.6	0.6	0.6	0.1	0.2	0.4	0.2	0.5	0.4	0.3	0.4	0.6	0.5	0.4	0.5	0.4	0.5	0.5	0.5
17-Mar-08	109	0.6	0.7	0.5	0.6	0.4	0.4	0.1	0.3	0.2	0.3	0.3	0.3	0.6	0.5	0.6	0.6	0.6	0.6	0.5	0.6
29-Mar-08	121	0.4	0.5	0.7	0.5	0.5	0.2	0.1	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.6	0.6	0.5
06-Apr-08	129	0.5	0.6	0.5	0.5	0.3	0.1	0.2	0.2	0.4	0.3	0.3	0.3	0.3	0.4	0.6	0.4	0.3	0.5	0.4	0.4
14-Apr-08	137	0.7	0.6	0.6	0.6	0.2	0.4	0.3	0.3	0.4	0.5	0.5	0.5	0.2	0.1	0.5	0.3	0.5	0.5	0.4	0.5
22-Apr-08	145	0.6	0.3	0.3	0.4	0.1	0.2	0.4	0.2	0.4	0.3	0.4	0.4	0.3	0.4	0.3	0.3	0.4	0.5	0.4	0.4
High strength influent; HRT of three days																					
29-Apr-08	152	0.2	0.3	0.3	0.3	0.1	0.0	0.2	0.1	0.2	0.3	0.4	0.3	0.3	0.2	0.1	0.2	0.5	0.3	0.4	0.4
05-May-08	158	0.3	0.5	0.4	0.4	0.0	0.3	0.4	0.2	0.4	0.4	0.5	0.4	0.3	0.2	0.4	0.3	0.3	0.3	0.2	0.3
09-May-08	162	0.7	0.5	0.3	0.5	0.1	0.2	0.3	0.2	0.2	0.5	0.6	0.4	0.3	0.2	0.1	0.2	0.2	0.3	0.1	0.2
15-May-08	168	0.4	0.4	0.3	0.4	0.4	0.3	0.2	0.3	0.6	0.4	0.3	0.4	0.3	0.2	0.2	0.2	0.4	0.3	0.3	0.3
17-May-08	170	0.4	0.5	0.4	0.4	0.0	0.3	0.4	0.2	0.4	0.5	0.7	0.5	0.2	0.3	0.1	0.2	0.2	0.3	0.3	0.3
20-May-08	173	0.5	0.6	0.4	0.5	0.2	0.3	0.5	0.3	0.2	0.4	0.3	0.3	0.2	0.3	0.4	0.3	0.0	0.1	0.2	0.1
24-May-08	177	0.3	0.4	0.2	0.3	0.2	0.3	0.2	0.2	0.5	0.5	0.2	0.4	0.3	0.3	0.4	0.3	0.2	0.3	0.1	0.2
26-May-08	179	0.4	0.4	0.3	0.4	0.4	0.2	0.3	0.3	0.6	0.3	0.2	0.4	0.3	0.1	0.0	0.1	0.3	0.3	0.4	0.3

Table A.6 (Continued)

Date	Days	Influent NO ₃ -N				Effluent NO ₃ -N M-UASB				Effluent NO ₃ -N T-UASB				Effluent NO ₃ -N M-HUASB				Effluent NO ₃ -N T-HUASB			
		(mg/L)				(mg/L)				(mg/L)				(mg/L)							
		S1	S2	S3	Ave	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.
High strength influent; HRT of two days																					
28-May-08	181	0.3	0.2	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.2	0.3	0.3	0.1	0.2	0.3	0.2	0.3	0.2	0.3	0.3
30-May-08	183	0.4	0.3	0.3	0.3	0.2	0.4	0.6	0.4	0.3	0.5	0.4	0.4	0.2	0.3	0.3	0.3	0.2	0.0	0.1	0.1
01-Jun-08	185	0.3	0.2	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.1	0.1	0.2	0.4	0.5	0.4	0.4	0.2	0.1	0.0	0.1
05-Jun-08	189	0.3	0.5	0.5	0.4	0.2	0.3	0.5	0.3	0.3	0.4	0.6	0.4	0.1	0.2	0.4	0.2	0.2	0.3	0.2	0.2
07-Jun-08	191	0.5	0.5	0.6	0.5	0.1	0.2	0.4	0.2	0.4	0.2	0.5	0.4	0.2	0.4	0.3	0.3	0.3	0.2	0.1	0.2
09-Jun-08	193	0.7	0.6	0.5	0.6	0.2	0.3	0.1	0.2	0.1	0.5	0.4	0.3	0.4	0.3	0.3	0.3	0.1	0.2	0.2	0.2
11-Jun-08	195	0.5	0.6	0.6	0.6	0.5	0.4	0.3	0.4	0.4	0.3	0.1	0.3	0.4	0.5	0.3	0.4	0.4	0.3	0.3	0.3
13-Jun-08	197	0.6	0.5	0.6	0.6	0.4	0.5	0.4	0.4	0.1	0.4	0.5	0.3	0.5	0.5	0.4	0.5	0.2	0.1	0.5	0.3
15-Jun-08	199	0.6	0.5	0.5	0.5	0.4	0.3	0.2	0.3	0.4	0.4	0.3	0.4	0.5	0.2	0.1	0.3	0.1	0.3	0.3	0.2

Table A.7 Influent and effluent TKN concentrations data in the UASB and HUASB reactors

Date	Days	Titrant (mL)	Titrant (mL)	Sample (mL)	TKN (mg/L)	Titrant (mL)	TKN (mg/L)	Titrant (mL)	TKN (mg/L)	Titrant (mL)	TKN (mg/L)	Titrant (mL)	TKN (mg/L)
		Influent	Blank		Influent	M-UASB	M-UASB	T-UASB	T-UASB	M-HUASB	M-HUASB	T-HUASB	T-HUASB
08-Dec-07	9	21.773	1.853	150	37.2	18.836	31.7	20.007	33.9				
12-Dec-07	13	20.592	0.984	150	36.6	19.659	34.9	19.868	35.3				
22-Dec-07	23	20.318	1.312	150	35.5	18.237	31.6	18.864	32.8				
03-Jan-08	35	19.971	1.117	150	35.2	18.783	33.0	18.579	32.6				
17-Jan-08	49	20.787	0.897	150	37.1	19.157	34.1	19.850	35.4				
31-Jan-08	63	21.296	1.223	150	37.5	19.232	33.6	20.113	35.3	18.263	31.8	19.497	34.1
20-Feb-08	83	32.321	2.840	150	55.0	28.655	48.2	28.880	48.6	26.214	43.6	28.470	47.8
01-Mar-08	93	30.152	0.924	150	54.6	28.334	51.2	29.768	53.8	27.397	49.4	28.345	51.2
17-Mar-08	109	30.677	0.887	150	55.6	26.388	47.6	29.122	52.7	27.753	50.1	29.235	52.9
06-Apr-08	129	31.879	0.972	150	57.7	32.896	59.6	29.957	54.1	28.520	51.4	29.672	53.6
22-Apr-08	145	31.351	0.845	150	56.9	31.231	56.7	30.481	55.3	28.863	52.3	30.294	55.0
09-May-08	162	29.431	1.126	150	52.8	25.852	46.2	27.337	48.9	26.832	48.0	27.492	49.2
17-May-08	170	28.451	1.223	150	50.8	25.187	44.7	26.472	47.1	25.539	45.4	25.963	46.2
24-May-08	177	28.364	1.149	150	50.8	25.944	46.3	27.747	49.6	26.354	47.0	26.881	48.0
05-Jun-08	189	27.974	1.173	150	50.0	26.749	47.7	26.948	48.1	26.539	47.3	26.554	47.4
13-Jun-08	197	27.738	1.281	150	49.4	26.783	47.6	26.977	48.0	26.142	46.4	26.459	47.0

Table A.8 Influent and effluent TP concentrations data in the UASB and HUASB reactors

Date	Days	Influent TP (mg/L)				Effluent TP M-UASB (mg/L)				Effluent TP T-UASB (mg/L)				Effluent TP M-HUASB (mg/L)				Effluent TP T-HUASB (mg/L)			
		S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.
Low strength influent; HRT of five days																					
02-Dec-07	3	4.5	4.7	5.3	4.8	18.6	17.5	18.8	18.3	11.3	10.6	11.2	11.0								
04-Dec-07	5	6.6	6.1	6.9	6.5	17.4	17.2	17.6	17.4	18.5	18.7	18.9	18.7								
08-Dec-07	9	6.9	7.7	7.5	7.4	16.6	16.4	15.9	16.3	20.1	20.2	21.3	20.5								
10-Dec-07	11	6.8	7.5	7.6	7.3	17.9	16.8	16.6	17.1	24.6	22.8	25.8	24.4								
12-Dec-07	13	6.8	7.5	7.1	7.1	17.1	17.5	17.3	17.3	22.4	23.8	28.3	24.8								
Low strength influent; HRT of three days																					
16-Dec-07	17	8.9	5.4	4.9	6.4	17.1	17.6	17.3	17.3	22.7	22.1	23.5	22.8								
18-Dec-07	19	8.1	9.5	7.8	8.5	15.4	16.0	14.5	15.3	16.7	15.8	18.1	16.9								
20-Dec-07	21	6.6	7.2	6.2	6.7	20.4	18.9	20.0	19.8	20.2	17.8	17.1	18.4								
22-Dec-07	23	5.2	6.6	5.2	5.7	14.8	15.5	13.7	14.7	14.3	14.0	14.1	14.1								
24-Dec-07	25	5.9	4.9	6.5	5.8	13.5	15.0	15.5	14.7	15.7	14.5	15.9	15.4								
26-Dec-07	27	8.4	6.5	7.7	7.5	15.0	14.2	14.8	14.7	19.2	18.1	19.0	18.8								
28-Dec-07	29	6.1	6.9	6.8	6.6	19.6	17.0	18.3	18.3	16.5	16.3	16.6	16.5								
01-Jan-08	33	6.8	6.5	6.8	6.7	16.7	17.7	16.4	16.9	16.2	16.6	15.6	16.1								
03-Jan-08	35	6.8	6.6	7.8	7.1	20.3	17.7	18.8	18.9	20.3	23.2	21.2	21.6								
07-Jan-08	39	7.1	7.3	6.5	7.0	19.8	20.1	22.0	20.6	22.2	23.5	21.2	22.3								
09-Jan-08	41	6.6	5.9	6.1	6.2	17.5	17.8	18.2	17.8	21.5	23.2	22.8	22.5								
11-Jan-08	43	6.8	6.5	6.9	6.7	19.2	18.5	17.2	18.3	22.8	22.2	20.1	21.7								
13-Jan-08	45	7.2	5.8	6.4	6.5	15.5	16.6	18.2	16.8	22.5	24.1	23.8	23.5								
15-Jan-08	47	6.6	6.7	6.8	6.7	17.5	18.5	17.9	18.0	23.5	23.8	24.5	23.9								
17-Jan-08	49	6.8	6.5	7.1	6.8	19.3	17.8	19.9	19.0	23.8	23.9	23.4	23.7								

Table A.8 (Continued)

Date	Days	Influent TP (mg/L)				Effluent TP M-UASB (mg/L)				Effluent TP T-UASB (mg/L)				Effluent TP M-HUASB (mg/L)				Effluent TP T-HUASB (mg/L)			
		S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.
Low strength influent; HRT of three days (continued)																					
21-Jan-08	53	6.8	6.7	5.8	6.4	19.5	18.2	20.1	19.3	22.1	22.3	22.7	22.4								
23-Jan-08	55	7.1	6.5	6.2	6.6	18.5	19.2	18.7	18.8	24.1	24.2	23.5	23.9								
27-Jan-08	59	6.4	6.8	5.2	6.1	19.5	18.7	20.5	19.6	22.5	20.2	22.1	21.6								
31-Jan-08	63	6.5	6.2	5.5	6.1	21.2	20.5	19.7	20.5	23.1	23.5	23.6	23.4	28.5	29.3	29.0	28.9	26.8	26.7	26.6	26.7
04-Feb-08	67	6.4	6.7	3.3	5.5	19.4	19.5	20.1	19.7	22.5	22.4	23.1	22.7	27.4	27.3	27.7	27.5	27.4	26.6	27.8	27.3
10-Feb-08	73	6.1	6.4	6.1	6.2	18.2	18.7	18.8	18.6	21.5	21.2	23.2	22.0	25.4	25.3	25.2	25.3	27.8	27.5	27.1	27.5
12-Feb-08	75	7.1	7.3	6.5	7.0	19.5	18.9	20.7	19.7	22.5	22.4	23.2	22.7	25.7	25.1	25.5	25.4	27.8	27.4	27.0	27.4
High strength influent; HRT of five days																					
14-Feb-08	77	13.2	13.0	13.1	13.1	19.7	19.6	19.6	19.6	21.4	21.5	21.5	21.5	28.3	28.8	29.1	28.7	26.8	26.9	26.9	26.9
16-Feb-08	79	12.8	12.7	12.9	12.8	17.1	17.0	17.4	17.2	18.6	18.6	18.3	18.5	28.4	28.5	28.7	28.5	31.6	31.6	31.3	31.5
20-Feb-08	83	12.7	13.1	12.3	12.7	15.9	16.7	15.8	16.1	17.0	17.6	17.0	17.2	29.0	28.5	28.2	28.6	33.8	35.0	34.3	34.4
24-Feb-08	87	14.1	13.8	14.6	14.2	18.2	18.4	18.6	18.4	17.9	18.0	18.2	18.0	29.8	29.9	30.1	29.9	32.5	33.1	32.5	32.7
01-Mar-08	93	13.6	13.8	14.0	13.8	20.0	19.0	19.6	19.5	21.2	22.0	21.1	21.4	30.7	30.5	30.4	30.5	35.9	35.7	35.8	35.8
High strength influent; HRT of four days																					
09-Mar-08	101	11.2	11.3	10.7	11.1	19.3	18.4	18.5	18.7	19.2	19.5	19.6	19.4	28.4	28.2	28.5	28.4	26.6	26.4	26.5	26.5
13-Mar-08	105	12.9	12.6	12.2	12.6	18.5	18.8	18.9	18.7	20.8	21.2	20.4	20.8	25.7	25.5	25.3	25.5	27.9	27.7	27.2	27.6
17-Mar-08	109	10.9	11.2	10.6	10.9	13.9	15.1	14.4	14.5	16.5	16.7	16.9	16.7	22.1	21.7	21.3	21.7	27.3	26.7	27.5	27.2
29-Mar-08	121	12.0	12.1	12.1	12.1	32.6	31.8	33.0	32.5	16.6	16.3	16.3	16.4	22.7	22.6	22.8	22.7	25.6	26.1	25.7	25.8
06-Apr-08	129	11.8	11.8	11.5	11.7	27.6	27.4	27.5	27.5	19.7	19.4	19.4	19.5	23.2	23.6	22.9	23.2	28.4	28.5	28.7	28.5
14-Apr-08	137	10.2	10.6	10.5	10.4	22.2	22.3	22.7	22.4	17.7	17.7	17.6	17.6	21.8	21.6	21.5	21.6	24.9	24.1	24.6	24.5
22-Apr-08	145	10.7	10.7	10.6	10.7	20.9	20.4	20.1	20.5	18.5	19.3	19.0	19.0	19.3	19.0	19.8	19.3	26.6	26.9	27.0	26.8

Table A.8 (Continued)

Date	Days	Influent TP (mg/L)				Effluent TP M-UASB (mg/L)				Effluent TP T-UASB (mg/L)				Effluent TP M-HUASB (mg/L)				Effluent TP T-HUASB (mg/L)			
		S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.	S1	S2	S3	Ave.
High strength influent; HRT of three days																					
29-Apr-08	152	11.0	11.3	11.4	11.2	18.1	18.0	18.4	18.2	15.3	15.4	15.6	15.4	22.5	21.5	22.1	22.0	27.1	27.6	27.2	27.3
05-May-08	158	12.1	12.9	12.6	12.5	14.7	14.5	14.3	14.5	16.0	15.8	16.3	16.1	24.8	24.9	25.1	24.9	28.2	28.7	29.0	28.6
09-May-08	162	11.9	12.4	12.0	12.1	14.9	14.8	14.6	14.8	19.1	18.9	19.0	19.0	24.0	24.3	23.7	24.0	27.3	27.0	26.9	27.1
15-May-08	168	10.9	10.8	10.6	10.8	14.3	13.7	14.5	14.2	17.4	16.6	17.8	17.2	23.6	23.7	23.9	23.7	29.6	29.7	29.9	29.7
17-May-08	170	11.1	10.9	11.2	11.1	14.1	13.8	14.6	14.2	18.3	18.9	18.3	18.5	22.8	22.9	22.3	22.7	27.6	27.4	27.5	27.5
20-May-08	173	12.5	12.3	12.2	12.3	14.3	13.3	13.9	13.8	18.8	18.4	18.0	18.4	21.6	21.9	22.0	21.8	26.7	26.1	26.5	26.4
24-May-08	177	11.6	11.7	12.1	11.8	15.6	15.7	15.1	15.5	18.3	18.1	17.6	18.0	22.2	22.6	21.8	22.2	26.9	26.1	26.6	26.5
26-May-08	179	11.3	12.1	11.2	11.5	15.4	15.2	14.7	15.1	18.7	18.5	19.0	18.7	23.3	23.6	23.7	23.5	25.7	25.8	26.0	25.8
High strength influent; HRT of two days																					
28-May-08	181	11.6	12.0	11.3	11.6	14.8	14.7	14.9	14.8	18.6	18.7	18.6	18.6	24.1	23.3	23.8	23.7	25.6	25.5	25.4	25.5
30-May-08	183	12.5	12.2	11.8	12.2	14.9	14.7	14.6	14.7	18.3	18.4	18.6	18.4	24.6	24.7	25.1	24.8	25.3	25.4	25.6	25.4
01-Jun-08	185	11.4	12.6	11.9	12.0	13.8	13.2	13.6	13.5	18.5	18.0	17.7	18.1	26.3	25.5	26.0	25.9	25.5	25.6	25.8	25.6
05-Jun-08	189	10.8	10.9	11.1	10.9	13.2	13.3	13.2	13.2	18.0	17.7	17.6	17.8	22.5	22.9	22.2	22.5	26.3	26.6	26.0	26.3
07-Jun-08	191	11.4	11.2	11.3	11.3	12.8	12.7	12.6	12.7	18.1	17.5	18.3	18.0	23.1	22.9	23.2	23.1	26.8	26.8	26.7	26.8
09-Jun-08	193	11.2	11.5	11.6	11.4	12.7	12.8	13.0	12.8	17.7	17.5	17.3	17.5	23.6	22.7	22.8	23.0	26.8	26.7	26.7	26.7
11-Jun-08	195	11.4	11.3	11.5	11.4	12.7	13.2	13.5	13.1	17.4	17.3	17.1	17.3	24.4	24.7	24.1	24.4	27.1	26.9	27.4	27.1
13-Jun-08	197	12.1	11.9	12.4	12.1	12.8	13.2	13.1	13.0	17.6	17.3	17.2	17.4	23.9	23.6	23.6	23.7	27.4	27.2	27.3	27.3
15-Jun-08	199	11.3	11.7	11.6	11.5	12.7	12.7	12.6	12.7	18.7	17.8	17.9	18.1	23.9	23.8	23.7	23.8	27.1	26.3	27.5	27.0

APPENDIX B STATISTICAL ANALYSIS

B.1 One-way ANOVA for COD concentration

This table provides a comparison of means for each operation of condition against each other operation condition. The important aspect to this table is a Sig. column that provides the exact significance for the difference between any two means, where this is less than 0.05, SPSS places a * symbol next to the value in the Mean Difference column, it is indicating a significant difference of the two samples being compared at significance level of 0.05.

Table B.1 One-way ANOVA Multiple Comparisons with COD removal as dependent variable (Tukey HSD Method)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
MUASB;5 day-low	MUASB;3 day-low	.7074	.93923	1.000	-2.7139	4.1286
	MUASB;5 day-high	-4.7745(*)	1.14156	.008	-8.9327	-.6162
	MUASB;4 day-high	.8114	1.17900	1.000	-3.4832	5.1061
	MUASB;3 day-high	7.6988(*)	1.06645	.000	3.8142	11.5835
	MUASB;2 day-high	13.5754(*)	1.11157	.000	9.5264	17.6244
	TUASB;5 day-low	7.3718(*)	1.38250	.000	2.3359	12.4077
	TUASB;3 day-low	4.2043(*)	.99056	.006	.5961	7.8125
	TUASB;5 day-high	-2.1545	1.14156	.956	-6.3127	2.0038
	TUASB;4 day-high	4.2764(*)	1.02105	.008	.5571	7.9957
	TUASB;3 day-high	12.7432(*)	1.11157	.000	8.6941	16.7922
	TUASB;2 day-high	19.7793(*)	1.22715	.000	15.3093	24.2493
	MHUASB;3 day-low	-.3740	1.22715	1.000	-4.8441	4.0960
	MTUASB;5 day-high	-5.9895(*)	1.14156	.000	-10.1477	-1.8312
	MHUASB;4 day-high	-1.7936	1.02105	.979	-5.5129	1.9257
	MHUASB;3 day-high	2.1929	1.02105	.862	-1.5264	5.9121
	MHUASB;2 day-high	5.2633(*)	1.08699	.001	1.3038	9.2228
	THUASB;3 day-low	21.7818(*)	1.38250	.000	16.7459	26.8177
	THUASB;5 day-high	.9955	1.14156	1.000	-3.1627	5.1538
	THUASB;4 day-high	6.1901(*)	1.04903	.000	2.3689	10.0113
	THUASB;3 day-high	8.2785(*)	1.04903	.000	4.4573	12.0997
	THUASB;2 day-high	13.7143(*)	1.08699	.000	9.7548	17.6738

* The mean difference is significant at the .05 level.

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
MUASB;3 day-low	MUASB;5 day-low	-.7074	.93923	1.000	-4.1286	2.7139
	MUASB;5 day-high	-5.4818(*)	.89178	.000	-8.7302	-2.2334
	MUASB;4 day-high	.1041	.93923	1.000	-3.3172	3.5253
	MUASB;3 day-high	6.9915(*)	.79335	.000	4.1016	9.8814
	MUASB;2 day-high	12.8680(*)	.85305	.000	9.7607	15.9754
	TUASB;5 day-low	6.6644(*)	1.18466	.000	2.3492	10.9797
	TUASB;3 day-low	3.4969(*)	.68797	.000	.9909	6.0029
	TUASB;5 day-high	-2.8618	.89178	.169	-6.1102	.3866
	TUASB;4 day-high	3.5691(*)	.73119	.000	.9056	6.2325
	TUASB;3 day-high	12.0358(*)	.85305	.000	8.9285	15.1431
	TUASB;2 day-high	19.0719(*)	.99899	.000	15.4330	22.7109
	MHUASB;3 day-low	-1.0814	.99899	1.000	-4.7204	2.5575
	MTUASB;5 day-high	-6.6968(*)	.89178	.000	-9.9452	-3.4484
	MHUASB;4 day-high	-2.5009	.73119	.097	-5.1644	.1625
	MHUASB;3 day-high	1.4855	.73119	.913	-1.1779	4.1489
	MHUASB;2 day-high	4.5559(*)	.82075	.000	1.5662	7.5456
	THUASB;3 day-low	21.0744(*)	1.18466	.000	16.7592	25.3897
	THUASB;5 day-high	.2882	.89178	1.000	-2.9602	3.5366
	THUASB;4 day-high	5.4828(*)	.76977	.000	2.6788	8.2867
	THUASB;3 day-high	7.5711(*)	.76977	.000	4.7671	10.3751
	THUASB;2 day-high	13.0069(*)	.82075	.000	10.0172	15.9966
MUASB;5 day-high	MUASB;5 day-low	4.7745(*)	1.14156	.008	.6162	8.9327
	MUASB;3 day-low	5.4818(*)	.89178	.000	2.2334	8.7302
	MUASB;4 day-high	5.5859(*)	1.14156	.000	1.4276	9.7442
	MUASB;3 day-high	12.4733(*)	1.02491	.000	8.7400	16.2066
	MUASB;2 day-high	18.3499(*)	1.07178	.000	14.4458	22.2540
	TUASB;5 day-low	12.1462(*)	1.35072	.000	7.2261	17.0664
	TUASB;3 day-low	8.9787(*)	.94569	.000	5.5340	12.4235
	TUASB;5 day-high	2.6200	1.10286	.724	-1.3973	6.6373
	TUASB;4 day-high	9.0509(*)	.97758	.000	5.4900	12.6118
	TUASB;3 day-high	17.5176(*)	1.07178	.000	13.6135	21.4217
	TUASB;2 day-high	24.5537(*)	1.19122	.000	20.2146	28.8929
	MHUASB;3 day-low	4.4004(*)	1.19122	.043	.0613	8.7396
	MTUASB;5 day-high	-1.2150	1.10286	1.000	-5.2323	2.8023
	MHUASB;4 day-high	2.9809	.97758	.246	-.5800	6.5418
	MHUASB;3 day-high	6.9673(*)	.97758	.000	3.4064	10.5283
	MHUASB;2 day-high	10.0377(*)	1.04626	.000	6.2266	13.8489
	THUASB;3 day-low	26.5562(*)	1.35072	.000	21.6361	31.4764
	THUASB;5 day-high	5.7700(*)	1.10286	.000	1.7527	9.7873
	THUASB;4 day-high	10.9646(*)	1.00677	.000	7.2973	14.6318
	THUASB;3 day-high	13.0529(*)	1.00677	.000	9.3857	16.7202
	THUASB;2 day-high	18.4887(*)	1.04626	.000	14.6776	22.2999

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
MUASB;4 day-high	MUASB;5 day-low	-.8114	1.17900	1.000	-5.1061	3.4832
	MUASB;3 day-low	-.1041	.93923	1.000	-3.5253	3.3172
	MUASB;5 day-high	-5.5859(*)	1.14156	.000	-9.7442	-1.4276
	MUASB;3 day-high	6.8874(*)	1.06645	.000	3.0027	10.7721
	MUASB;2 day-high	12.7640(*)	1.11157	.000	8.7149	16.8130
	TUASB;5 day-low	6.5604(*)	1.38250	.001	1.5244	11.5963
	TUASB;3 day-low	3.3929	.99056	.095	-.2154	7.0011
	TUASB;5 day-high	-2.9659	1.14156	.557	-7.1242	1.1924
	TUASB;4 day-high	3.4650	1.02105	.104	-.2543	7.1843
	TUASB;3 day-high	11.9317(*)	1.11157	.000	7.8827	15.9808
	TUASB;2 day-high	18.9679(*)	1.22715	.000	14.4978	23.4379
	MHUASB;3 day-low	-1.1855	1.22715	1.000	-5.6555	3.2845
	MTUASB;5 day-high	-6.8009(*)	1.14156	.000	-10.9592	-2.6426
	MHUASB;4 day-high	-2.6050	1.02105	.593	-6.3243	1.1143
	MHUASB;3 day-high	1.3814	1.02105	.999	-2.3379	5.1007
	MHUASB;2 day-high	4.4519(*)	1.08699	.011	.4924	8.4113
	THUASB;3 day-low	20.9704(*)	1.38250	.000	15.9344	26.0063
	THUASB;5 day-high	.1841	1.14156	1.000	-3.9742	4.3424
	THUASB;4 day-high	5.3787(*)	1.04903	.000	1.5575	9.1999
	THUASB;3 day-high	7.4670(*)	1.04903	.000	3.6458	11.2882
	THUASB;2 day-high	12.9029(*)	1.08699	.000	8.9434	16.8623
MUASB;3 day-high	MUASB;5 day-low	-7.6988(*)	1.06645	.000	-11.5835	-3.8142
	MUASB;3 day-low	-6.9915(*)	.79335	.000	-9.8814	-4.1016
	MUASB;5 day-high	-12.4733(*)	1.02491	.000	-16.2066	-8.7400
	MUASB;4 day-high	-6.8874(*)	1.06645	.000	-10.7721	-3.0027
	MUASB;2 day-high	5.8766(*)	.99139	.000	2.2653	9.4878
	TUASB;5 day-low	-.3270	1.28786	1.000	-5.0182	4.3641
	TUASB;3 day-low	-3.4945(*)	.85351	.011	-6.6035	-.3855
	TUASB;5 day-high	-9.8533(*)	1.02491	.000	-13.5866	-6.1200
	TUASB;4 day-high	-3.4224(*)	.88871	.025	-6.6596	-.1852
	TUASB;3 day-high	5.0443(*)	.99139	.000	1.4331	8.6556
	TUASB;2 day-high	12.0805(*)	1.11944	.000	8.0028	16.1582
	MHUASB;3 day-low	-8.0729(*)	1.11944	.000	-12.1506	-3.9952
	MTUASB;5 day-high	-13.6883(*)	1.02491	.000	-17.4216	-9.9550
	MHUASB;4 day-high	-9.4924(*)	.88871	.000	-12.7296	-6.2552
	MHUASB;3 day-high	-5.5060(*)	.88871	.000	-8.7432	-2.2688
	MHUASB;2 day-high	-2.4355	.96375	.612	-5.9461	1.0750
	THUASB;3 day-low	14.0830(*)	1.28786	.000	9.3918	18.7741
	THUASB;5 day-high	-6.7033(*)	1.02491	.000	-10.4366	-2.9700
	THUASB;4 day-high	-1.5087	.92072	.991	-4.8625	1.8451
	THUASB;3 day-high	.5796	.92072	1.000	-2.7742	3.9334
	THUASB;2 day-high	6.0155(*)	.96375	.000	2.5049	9.5260

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
MUASB;2 day-high	MUASB;5 day-low	-13.5754(*)	1.11157	.000	-17.6244	-9.5264
	MUASB;3 day-low	-12.8680(*)	.85305	.000	-15.9754	-9.7607
	MUASB;5 day-high	-18.3499(*)	1.07178	.000	-22.2540	-14.4458
	MUASB;4 day-high	-12.7640(*)	1.11157	.000	-16.8130	-8.7149
	MUASB;3 day-high	-5.8766(*)	.99139	.000	-9.4878	-2.2653
	TUASB;5 day-low	-6.2036(*)	1.32547	.001	-11.0318	-1.3754
	TUASB;3 day-low	-9.3711(*)	.90926	.000	-12.6832	-6.0590
	TUASB;5 day-high	-15.7299(*)	1.07178	.000	-19.6340	-11.8258
	TUASB;4 day-high	-9.2990(*)	.94238	.000	-12.7317	-5.8662
	TUASB;3 day-high	-.8322	1.03978	1.000	-4.6198	2.9553
	TUASB;2 day-high	6.2039(*)	1.16251	.000	1.9693	10.4385
	MHUASB;3 day-low	-13.9494(*)	1.16251	.000	-18.1840	-9.7149
	MTUASB;5 day-high	-19.5649(*)	1.07178	.000	-23.4690	-15.6608
	MHUASB;4 day-high	-15.3690(*)	.94238	.000	-18.8017	-11.9362
	MHUASB;3 day-high	-11.3825(*)	.94238	.000	-14.8153	-7.9498
	MHUASB;2 day-high	-8.3121(*)	1.01346	.000	-12.0037	-4.6205
	THUASB;3 day-low	8.2064(*)	1.32547	.000	3.3782	13.0346
	THUASB;5 day-high	-12.5799(*)	1.07178	.000	-16.4840	-8.6758
	THUASB;4 day-high	-7.3853(*)	.97263	.000	-10.9282	-3.8424
	THUASB;3 day-high	-5.2969(*)	.97263	.000	-8.8399	-1.7540
	THUASB;2 day-high	.1389	1.01346	1.000	-3.5527	3.8305
TUASB;5 day-low	MUASB;5 day-low	-7.3718(*)	1.38250	.000	-12.4077	-2.3359
	MUASB;3 day-low	-6.6644(*)	1.18466	.000	-10.9797	-2.3492
	MUASB;5 day-high	-12.1462(*)	1.35072	.000	-17.0664	-7.2261
	MUASB;4 day-high	-6.5604(*)	1.38250	.001	-11.5963	-1.5244
	MUASB;3 day-high	.3270	1.28786	1.000	-4.3641	5.0182
	MUASB;2 day-high	6.2036(*)	1.32547	.001	1.3754	11.0318
	TUASB;3 day-low	-3.1675	1.22576	.568	-7.6325	1.2975
	TUASB;5 day-high	-9.5263(*)	1.35072	.000	-14.4464	-4.6061
	TUASB;4 day-high	-3.0954	1.25052	.651	-7.6505	1.4598
	TUASB;3 day-high	5.3714(*)	1.32547	.013	.5432	10.1996
	TUASB;2 day-high	12.4075(*)	1.42378	.000	7.2212	17.5938
	MHUASB;3 day-low	-7.7458(*)	1.42378	.000	-12.9321	-2.5595
	MTUASB;5 day-high	-13.3613(*)	1.35072	.000	-18.2814	-8.4411
	MHUASB;4 day-high	-9.1654(*)	1.25052	.000	-13.7205	-4.6102
	MHUASB;3 day-high	-5.1789(*)	1.25052	.009	-9.7341	-.6238
	MHUASB;2 day-high	-2.1085	1.30492	.992	-6.8618	2.6448
	THUASB;3 day-low	14.4100(*)	1.55967	.000	8.7287	20.0913
	THUASB;5 day-high	-6.3763(*)	1.35072	.001	-11.2964	-1.4561
	THUASB;4 day-high	-1.1817	1.27347	1.000	-5.8204	3.4571
	THUASB;3 day-high	.9067	1.27347	1.000	-3.7321	5.5454
	THUASB;2 day-high	6.3425(*)	1.30492	.000	1.5892	11.0958

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TUASB;3 day-low	MUASB;5 day-low	-4.2043(*)	.99056	.006	-7.8125	-.5961
	MUASB;3 day-low	-3.4969(*)	.68797	.000	-6.0029	-.9909
	MUASB;5 day-high	-8.9787(*)	.94569	.000	-12.4235	-5.5340
	MUASB;4 day-high	-3.3929	.99056	.095	-7.0011	.2154
	MUASB;3 day-high	3.4945(*)	.85351	.011	.3855	6.6035
	MUASB;2 day-high	9.3711(*)	.90926	.000	6.0590	12.6832
	TUASB;5 day-low	3.1675	1.22576	.568	-1.2975	7.6325
	TUASB;5 day-high	-6.3588(*)	.94569	.000	-9.8035	-2.9140
	TUASB;4 day-high	.0721	.79605	1.000	-2.8276	2.9719
	TUASB;3 day-high	8.5389(*)	.90926	.000	5.2268	11.8510
	TUASB;2 day-high	15.5750(*)	1.04740	.000	11.7597	19.3903
	MHUASB;3 day-low	-4.5783(*)	1.04740	.004	-8.3936	-.7631
	MTUASB;5 day-high	-10.1938(*)	.94569	.000	-13.6385	-6.7490
	MHUASB;4 day-high	-5.9979(*)	.79605	.000	-8.8976	-3.0981
	MHUASB;3 day-high	-2.0114	.79605	.612	-4.9111	.8883
	MHUASB;2 day-high	1.0590	.87904	1.000	-2.1430	4.2610
	THUASB;3 day-low	17.5775(*)	1.22576	.000	13.1125	22.0425
	THUASB;5 day-high	-3.2088	.94569	.104	-6.6535	.2360
	THUASB;4 day-high	1.9858	.83164	.715	-1.0435	5.0152
	THUASB;3 day-high	4.0742(*)	.83164	.000	1.0448	7.1035
	THUASB;2 day-high	9.5100(*)	.87904	.000	6.3080	12.7120
TUASB;5 day-high	MUASB;5 day-low	2.1545	1.14156	.956	-2.0038	6.3127
	MUASB;3 day-low	2.8618	.89178	.169	-.3866	6.1102
	MUASB;5 day-high	-2.6200	1.10286	.724	-6.6373	1.3973
	MUASB;4 day-high	2.9659	1.14156	.557	-1.1924	7.1242
	MUASB;3 day-high	9.8533(*)	1.02491	.000	6.1200	13.5866
	MUASB;2 day-high	15.7299(*)	1.07178	.000	11.8258	19.6340
	TUASB;5 day-low	9.5263(*)	1.35072	.000	4.6061	14.4464
	TUASB;3 day-low	6.3588(*)	.94569	.000	2.9140	9.8035
	TUASB;4 day-high	6.4309(*)	.97758	.000	2.8700	9.9918
	TUASB;3 day-high	14.8976(*)	1.07178	.000	10.9935	18.8017
	TUASB;2 day-high	21.9338(*)	1.19122	.000	17.5946	26.2729
	MHUASB;3 day-low	1.7804	1.19122	.997	-2.5587	6.1196
	MTUASB;5 day-high	-3.8350	1.10286	.082	-7.8523	.1823
	MHUASB;4 day-high	.3609	.97758	1.000	-3.2000	3.9218
	MHUASB;3 day-high	4.3473(*)	.97758	.003	.7864	7.9083
	MHUASB;2 day-high	7.4178(*)	1.04626	.000	3.6066	11.2289
	THUASB;3 day-low	23.9363(*)	1.35072	.000	19.0161	28.8564
	THUASB;5 day-high	3.1500	1.10286	.365	-.8673	7.1673
	THUASB;4 day-high	8.3446(*)	1.00677	.000	4.6773	12.0118
	THUASB;3 day-high	10.4329(*)	1.00677	.000	6.7657	14.1002
	THUASB;2 day-high	15.8688(*)	1.04626	.000	12.0576	19.6799

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TUASB;4 day-high	MUASB;5 day-low	-4.2764(*)	1.02105	.008	-7.9957	-.5571
	MUASB;3 day-low	-3.5691(*)	.73119	.000	-6.2325	-.9056
	MUASB;5 day-high	-9.0509(*)	.97758	.000	-12.6118	-5.4900
	MUASB;4 day-high	-3.4650	1.02105	.104	-7.1843	.2543
	MUASB;3 day-high	3.4224(*)	.88871	.025	.1852	6.6596
	MUASB;2 day-high	9.2990(*)	.94238	.000	5.8662	12.7317
	TUASB;5 day-low	3.0954	1.25052	.651	-1.4598	7.6505
	TUASB;3 day-low	-.0721	.79605	1.000	-2.9719	2.8276
	TUASB;5 day-high	-6.4309(*)	.97758	.000	-9.9918	-2.8700
	TUASB;3 day-high	8.4667(*)	.94238	.000	5.0340	11.8995
	TUASB;2 day-high	15.5029(*)	1.07628	.000	11.5824	19.4233
	MHUASB;3 day-low	-4.6505(*)	1.07628	.005	-8.5709	-.7300
	MTUASB;5 day-high	-10.2659(*)	.97758	.000	-13.8268	-6.7050
	MHUASB;4 day-high	-6.0700(*)	.83368	.000	-9.1068	-3.0332
	MHUASB;3 day-high	-2.0836	.83368	.633	-5.1204	.9532
	MHUASB;2 day-high	.9869	.91325	1.000	-2.3398	4.3135
	THUASB;3 day-low	17.5054(*)	1.25052	.000	12.9502	22.0605
	THUASB;5 day-high	-3.2809	.97758	.115	-6.8418	.2800
	THUASB;4 day-high	1.9137	.86772	.832	-1.2471	5.0745
	THUASB;3 day-high	4.0020(*)	.86772	.001	.8412	7.1628
	THUASB;2 day-high	9.4379(*)	.91325	.000	6.1112	12.7645
TUASB;3 day-high	MUASB;5 day-low	-12.7432(*)	1.11157	.000	-16.7922	-8.6941
	MUASB;3 day-low	-12.0358(*)	.85305	.000	-15.1431	-8.9285
	MUASB;5 day-high	-17.5176(*)	1.07178	.000	-21.4217	-13.6135
	MUASB;4 day-high	-11.9317(*)	1.11157	.000	-15.9808	-7.8827
	MUASB;3 day-high	-5.0443(*)	.99139	.000	-8.6556	-1.4331
	MUASB;2 day-high	.8322	1.03978	1.000	-2.9553	4.6198
	TUASB;5 day-low	-5.3714(*)	1.32547	.013	-10.1996	-.5432
	TUASB;3 day-low	-8.5389(*)	.90926	.000	-11.8510	-5.2268
	TUASB;5 day-high	-14.8976(*)	1.07178	.000	-18.8017	-10.9935
	TUASB;4 day-high	-8.4667(*)	.94238	.000	-11.8995	-5.0340
	TUASB;2 day-high	7.0361(*)	1.16251	.000	2.8015	11.2707
	MHUASB;3 day-low	-13.1172(*)	1.16251	.000	-17.3518	-8.8826
	MTUASB;5 day-high	-18.7326(*)	1.07178	.000	-22.6367	-14.8285
	MHUASB;4 day-high	-14.5367(*)	.94238	.000	-17.9695	-11.1040
	MHUASB;3 day-high	-10.5503(*)	.94238	.000	-13.9831	-7.1176
	MHUASB;2 day-high	-7.4799(*)	1.01346	.000	-11.1715	-3.7883
	THUASB;3 day-low	9.0386(*)	1.32547	.000	4.2104	13.8668
	THUASB;5 day-high	-11.7476(*)	1.07178	.000	-15.6517	-7.8435
	THUASB;4 day-high	-6.5531(*)	.97263	.000	-10.0960	-3.0101
	THUASB;3 day-high	-4.4647(*)	.97263	.002	-8.0076	-.9218
	THUASB;2 day-high	.9711	1.01346	1.000	-2.7205	4.6627

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TUASB;2 day-high	MUASB;5 day-low	-19.7793(*)	1.22715	.000	-24.2493	-15.3093
	MUASB;3 day-low	-19.0719(*)	.99899	.000	-22.7109	-15.4330
	MUASB;5 day-high	-24.5537(*)	1.19122	.000	-28.8929	-20.2146
	MUASB;4 day-high	-18.9679(*)	1.22715	.000	-23.4379	-14.4978
	MUASB;3 day-high	-12.0805(*)	1.11944	.000	-16.1582	-8.0028
	MUASB;2 day-high	-6.2039(*)	1.16251	.000	-10.4385	-1.9693
	TUASB;5 day-low	-12.4075(*)	1.42378	.000	-17.5938	-7.2212
	TUASB;3 day-low	-15.5750(*)	1.04740	.000	-19.3903	-11.7597
	TUASB;5 day-high	-21.9338(*)	1.19122	.000	-26.2729	-17.5946
	TUASB;4 day-high	-15.5029(*)	1.07628	.000	-19.4233	-11.5824
	TUASB;3 day-high	-7.0361(*)	1.16251	.000	-11.2707	-2.8015
	MHUASB;3 day-low	-20.1533(*)	1.27347	.000	-24.7921	-15.5146
	MTUASB;5 day-high	-25.7688(*)	1.19122	.000	-30.1079	-21.4296
	MHUASB;4 day-high	-21.5729(*)	1.07628	.000	-25.4933	-17.6524
	MHUASB;3 day-high	-17.5864(*)	1.07628	.000	-21.5069	-13.6660
	MHUASB;2 day-high	-14.5160(*)	1.13903	.000	-18.6650	-10.3670
	THUASB;3 day-low	2.0025	1.42378	.999	-3.1838	7.1888
	THUASB;5 day-high	-18.7838(*)	1.19122	.000	-23.1229	-14.4446
	THUASB;4 day-high	-13.5892(*)	1.10286	.000	-17.6064	-9.5719
	THUASB;3 day-high	-11.5008(*)	1.10286	.000	-15.5181	-7.4836
	THUASB;2 day-high	-6.0650(*)	1.13903	.000	-10.2140	-1.9160
MHUASB;3 day-low	MUASB;5 day-low	.3740	1.22715	1.000	-4.0960	4.8441
	MUASB;3 day-low	1.0814	.99899	1.000	-2.5575	4.7204
	MUASB;5 day-high	-4.4004(*)	1.19122	.043	-8.7396	-.0613
	MUASB;4 day-high	1.1855	1.22715	1.000	-3.2845	5.6555
	MUASB;3 day-high	8.0729(*)	1.11944	.000	3.9952	12.1506
	MUASB;2 day-high	13.9494(*)	1.16251	.000	9.7149	18.1840
	TUASB;5 day-low	7.7458(*)	1.42378	.000	2.5595	12.9321
	TUASB;3 day-low	4.5783(*)	1.04740	.004	.7631	8.3936
	TUASB;5 day-high	-1.7804	1.19122	.997	-6.1196	2.5587
	TUASB;4 day-high	4.6505(*)	1.07628	.005	.7300	8.5709
	TUASB;3 day-high	13.1172(*)	1.16251	.000	8.8826	17.3518
	TUASB;2 day-high	20.1533(*)	1.27347	.000	15.5146	24.7921
	MTUASB;5 day-high	-5.6154(*)	1.19122	.001	-9.9546	-1.2763
	MHUASB;4 day-high	-1.4195	1.07628	.999	-5.3400	2.5009
	MHUASB;3 day-high	2.5669	1.07628	.717	-1.3536	6.4874
	MHUASB;2 day-high	5.6373(*)	1.13903	.000	1.4883	9.7864
	THUASB;3 day-low	22.1558(*)	1.42378	.000	16.9695	27.3421
	THUASB;5 day-high	1.3696	1.19122	1.000	-2.9696	5.7087
	THUASB;4 day-high	6.5642(*)	1.10286	.000	2.5469	10.5814
	THUASB;3 day-high	8.6525(*)	1.10286	.000	4.6352	12.6698
	THUASB;2 day-high	14.0883(*)	1.13903	.000	9.9393	18.2374

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
MTUASB;5 day-high	MUASB;5 day-low	5.9895(*)	1.14156	.000	1.8312	10.1477
	MUASB;3 day-low	6.6968(*)	.89178	.000	3.4484	9.9452
	MUASB;5 day-high	1.2150	1.10286	1.000	-2.8023	5.2323
	MUASB;4 day-high	6.8009(*)	1.14156	.000	2.6426	10.9592
	MUASB;3 day-high	13.6883(*)	1.02491	.000	9.9550	17.4216
	MUASB;2 day-high	19.5649(*)	1.07178	.000	15.6608	23.4690
	TUASB;5 day-low	13.3613(*)	1.35072	.000	8.4411	18.2814
	TUASB;3 day-low	10.1938(*)	.94569	.000	6.7490	13.6385
	TUASB;5 day-high	3.8350	1.10286	.082	-.1823	7.8523
	TUASB;4 day-high	10.2659(*)	.97758	.000	6.7050	13.8268
	TUASB;3 day-high	18.7326(*)	1.07178	.000	14.8285	22.6367
	TUASB;2 day-high	25.7688(*)	1.19122	.000	21.4296	30.1079
	MHUASB;3 day-low	5.6154(*)	1.19122	.001	1.2763	9.9546
	MHUASB;4 day-high	4.1959(*)	.97758	.005	.6350	7.7568
	MHUASB;3 day-high	8.1823(*)	.97758	.000	4.6214	11.7433
	MHUASB;2 day-high	11.2528(*)	1.04626	.000	7.4416	15.0639
	THUASB;3 day-low	27.7713(*)	1.35072	.000	22.8511	32.6914
	THUASB;5 day-high	6.9850(*)	1.10286	.000	2.9677	11.0023
	THUASB;4 day-high	12.1796(*)	1.00677	.000	8.5123	15.8468
	THUASB;3 day-high	14.2679(*)	1.00677	.000	10.6007	17.9352
	THUASB;2 day-high	19.7038(*)	1.04626	.000	15.8926	23.5149
MHUASB;4 day-high	MUASB;5 day-low	1.7936	1.02105	.979	-1.9257	5.5129
	MUASB;3 day-low	2.5009	.73119	.097	-.1625	5.1644
	MUASB;5 day-high	-2.9809	.97758	.246	-6.5418	.5800
	MUASB;4 day-high	2.6050	1.02105	.593	-1.1143	6.3243
	MUASB;3 day-high	9.4924(*)	.88871	.000	6.2552	12.7296
	MUASB;2 day-high	15.3690(*)	.94238	.000	11.9362	18.8017
	TUASB;5 day-low	9.1654(*)	1.25052	.000	4.6102	13.7205
	TUASB;3 day-low	5.9979(*)	.79605	.000	3.0981	8.8976
	TUASB;5 day-high	-.3609	.97758	1.000	-3.9218	3.2000
	TUASB;4 day-high	6.0700(*)	.83368	.000	3.0332	9.1068
	TUASB;3 day-high	14.5367(*)	.94238	.000	11.1040	17.9695
	TUASB;2 day-high	21.5729(*)	1.07628	.000	17.6524	25.4933
	MHUASB;3 day-low	1.4195	1.07628	.999	-2.5009	5.3400
	MTUASB;5 day-high	-4.1959(*)	.97758	.005	-7.7568	-.6350
	MHUASB;3 day-high	3.9864(*)	.83368	.001	.9496	7.0232
	MHUASB;2 day-high	7.0569(*)	.91325	.000	3.7302	10.3835
	THUASB;3 day-low	23.5754(*)	1.25052	.000	19.0202	28.1305
	THUASB;5 day-high	2.7891	.97758	.367	-.7718	6.3500
	THUASB;4 day-high	7.9837(*)	.86772	.000	4.8229	11.1445
	THUASB;3 day-high	10.0720(*)	.86772	.000	6.9112	13.2328
	THUASB;2 day-high	15.5079(*)	.91325	.000	12.1812	18.8345

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
MHUASB;3 day-high	MUASB;5 day-low	-2.1929	1.02105	.862	-5.9121	1.5264
	MUASB;3 day-low	-1.4855	.73119	.913	-4.1489	1.1779
	MUASB;5 day-high	-6.9673(*)	.97758	.000	-10.5283	-3.4064
	MUASB;4 day-high	-1.3814	1.02105	.999	-5.1007	2.3379
	MUASB;3 day-high	5.5060(*)	.88871	.000	2.2688	8.7432
	MUASB;2 day-high	11.3825(*)	.94238	.000	7.9498	14.8153
	TUASB;5 day-low	5.1789(*)	1.25052	.009	.6238	9.7341
	TUASB;3 day-low	2.0114	.79605	.612	-.8883	4.9111
	TUASB;5 day-high	-4.3473(*)	.97758	.003	-7.9083	-.7864
	TUASB;4 day-high	2.0836	.83368	.633	-.9532	5.1204
	TUASB;3 day-high	10.5503(*)	.94238	.000	7.1176	13.9831
	TUASB;2 day-high	17.5864(*)	1.07628	.000	13.6660	21.5069
	MHUASB;3 day-low	-2.5669	1.07628	.717	-6.4874	1.3536
	MTUASB;5 day-high	-8.1823(*)	.97758	.000	-11.7433	-4.6214
	MHUASB;4 day-high	-3.9864(*)	.83368	.001	-7.0232	-.9496
	MHUASB;2 day-high	3.0704	.91325	.113	-.2562	6.3971
	THUASB;3 day-low	19.5889(*)	1.25052	.000	15.0338	24.1441
	THUASB;5 day-high	-1.1973	.97758	1.000	-4.7583	2.3636
	THUASB;4 day-high	3.9973(*)	.86772	.001	.8365	7.1580
	THUASB;3 day-high	6.0856(*)	.86772	.000	2.9248	9.2464
	THUASB;2 day-high	11.5214(*)	.91325	.000	8.1948	14.8481
MHUASB;2 day-high	MUASB;5 day-low	-5.2633(*)	1.08699	.001	-9.2228	-1.3038
	MUASB;3 day-low	-4.5559(*)	.82075	.000	-7.5456	-1.5662
	MUASB;5 day-high	-10.0377(*)	1.04626	.000	-13.8489	-6.2266
	MUASB;4 day-high	-4.4519(*)	1.08699	.011	-8.4113	-.4924
	MUASB;3 day-high	2.4355	.96375	.612	-1.0750	5.9461
	MUASB;2 day-high	8.3121(*)	1.01346	.000	4.6205	12.0037
	TUASB;5 day-low	2.1085	1.30492	.992	-2.6448	6.8618
	TUASB;3 day-low	-1.0590	.87904	1.000	-4.2610	2.1430
	TUASB;5 day-high	-7.4178(*)	1.04626	.000	-11.2289	-3.6066
	TUASB;4 day-high	-.9869	.91325	1.000	-4.3135	2.3398
	TUASB;3 day-high	7.4799(*)	1.01346	.000	3.7883	11.1715
	TUASB;2 day-high	14.5160(*)	1.13903	.000	10.3670	18.6650
	MHUASB;3 day-low	-5.6373(*)	1.13903	.000	-9.7864	-1.4883
	MTUASB;5 day-high	-11.2528(*)	1.04626	.000	-15.0639	-7.4416
	MHUASB;4 day-high	-7.0569(*)	.91325	.000	-10.3835	-3.7302
	MHUASB;3 day-high	-3.0704	.91325	.113	-6.3971	.2562
	THUASB;3 day-low	16.5185(*)	1.30492	.000	11.7652	21.2718
	THUASB;5 day-high	-4.2678(*)	1.04626	.011	-8.0789	-.4566
	THUASB;4 day-high	.9268	.94443	1.000	-2.5134	4.3670
	THUASB;3 day-high	3.0152	.94443	.176	-.4250	6.4554
	THUASB;2 day-high	8.4510(*)	.98642	.000	4.8578	12.0442

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
THUASB;3 day-low	MUASB;5 day-low	-21.7818(*)	1.38250	.000	-26.8177	-16.7459
	MUASB;3 day-low	-21.0744(*)	1.18466	.000	-25.3897	-16.7592
	MUASB;5 day-high	-26.5562(*)	1.35072	.000	-31.4764	-21.6361
	MUASB;4 day-high	-20.9704(*)	1.38250	.000	-26.0063	-15.9344
	MUASB;3 day-high	-14.0830(*)	1.28786	.000	-18.7741	-9.3918
	MUASB;2 day-high	-8.2064(*)	1.32547	.000	-13.0346	-3.3782
	TUASB;5 day-low	-14.4100(*)	1.55967	.000	-20.0913	-8.7287
	TUASB;3 day-low	-17.5775(*)	1.22576	.000	-22.0425	-13.1125
	TUASB;5 day-high	-23.9363(*)	1.35072	.000	-28.8564	-19.0161
	TUASB;4 day-high	-17.5054(*)	1.25052	.000	-22.0605	-12.9502
	TUASB;3 day-high	-9.0386(*)	1.32547	.000	-13.8668	-4.2104
	TUASB;2 day-high	-2.0025	1.42378	.999	-7.1888	3.1838
	MHUASB;3 day-low	-22.1558(*)	1.42378	.000	-27.3421	-16.9695
	MTUASB;5 day-high	-27.7713(*)	1.35072	.000	-32.6914	-22.8511
	MHUASB;4 day-high	-23.5754(*)	1.25052	.000	-28.1305	-19.0202
	MHUASB;3 day-high	-19.5889(*)	1.25052	.000	-24.1441	-15.0338
	MHUASB;2 day-high	-16.5185(*)	1.30492	.000	-21.2718	-11.7652
	THUASB;5 day-high	-20.7863(*)	1.35072	.000	-25.7064	-15.8661
	THUASB;4 day-high	-15.5917(*)	1.27347	.000	-20.2304	-10.9529
	THUASB;3 day-high	-13.5033(*)	1.27347	.000	-18.1421	-8.8646
	THUASB;2 day-high	-8.0675(*)	1.30492	.000	-12.8208	-3.3142
THUASB;5 day-high	MUASB;5 day-low	-.9955	1.14156	1.000	-5.1538	3.1627
	MUASB;3 day-low	-.2882	.89178	1.000	-3.5366	2.9602
	MUASB;5 day-high	-5.7700(*)	1.10286	.000	-9.7873	-1.7527
	MUASB;4 day-high	-.1841	1.14156	1.000	-4.3424	3.9742
	MUASB;3 day-high	6.7033(*)	1.02491	.000	2.9700	10.4366
	MUASB;2 day-high	12.5799(*)	1.07178	.000	8.6758	16.4840
	TUASB;5 day-low	6.3763(*)	1.35072	.001	1.4561	11.2964
	TUASB;3 day-low	3.2088	.94569	.104	-.2360	6.6535
	TUASB;5 day-high	-3.1500	1.10286	.365	-7.1673	.8673
	TUASB;4 day-high	3.2809	.97758	.115	-.2800	6.8418
	TUASB;3 day-high	11.7476(*)	1.07178	.000	7.8435	15.6517
	TUASB;2 day-high	18.7838(*)	1.19122	.000	14.4446	23.1229
	MHUASB;3 day-low	-1.3696	1.19122	1.000	-5.7087	2.9696
	MTUASB;5 day-high	-6.9850(*)	1.10286	.000	-11.0023	-2.9677
	MHUASB;4 day-high	-2.7891	.97758	.367	-6.3500	.7718
	MHUASB;3 day-high	1.1973	.97758	1.000	-2.3636	4.7583
	MHUASB;2 day-high	4.2678(*)	1.04626	.011	.4566	8.0789
	THUASB;3 day-low	20.7863(*)	1.35072	.000	15.8661	25.7064
	THUASB;4 day-high	5.1946(*)	1.00677	.000	1.5273	8.8618
	THUASB;3 day-high	7.2829(*)	1.00677	.000	3.6157	10.9502
	THUASB;2 day-high	12.7188(*)	1.04626	.000	8.9076	16.5299

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
THUASB;4 day-high	MUASB;5 day-low	-6.1901(*)	1.04903	.000	-10.0113	-2.3689
	MUASB;3 day-low	-5.4828(*)	.76977	.000	-8.2867	-2.6788
	MUASB;5 day-high	-10.9646(*)	1.00677	.000	-14.6318	-7.2973
	MUASB;4 day-high	-5.3787(*)	1.04903	.000	-9.1999	-1.5575
	MUASB;3 day-high	1.5087	.92072	.991	-1.8451	4.8625
	MUASB;2 day-high	7.3853(*)	.97263	.000	3.8424	10.9282
	TUASB;5 day-low	1.1817	1.27347	1.000	-3.4571	5.8204
	TUASB;3 day-low	-1.9858	.83164	.715	-5.0152	1.0435
	TUASB;5 day-high	-8.3446(*)	1.00677	.000	-12.0118	-4.6773
	TUASB;4 day-high	-1.9137	.86772	.832	-5.0745	1.2471
	TUASB;3 day-high	6.5531(*)	.97263	.000	3.0101	10.0960
	TUASB;2 day-high	13.5892(*)	1.10286	.000	9.5719	17.6064
	MHUASB;3 day-low	-6.5642(*)	1.10286	.000	-10.5814	-2.5469
	MTUASB;5 day-high	-12.1796(*)	1.00677	.000	-15.8468	-8.5123
	MHUASB;4 day-high	-7.9837(*)	.86772	.000	-11.1445	-4.8229
	MHUASB;3 day-high	-3.9973(*)	.86772	.001	-7.1580	-.8365
	MHUASB;2 day-high	-.9268	.94443	1.000	-4.3670	2.5134
	THUASB;3 day-low	15.5917(*)	1.27347	.000	10.9529	20.2304
	THUASB;5 day-high	-5.1946(*)	1.00677	.000	-8.8618	-1.5273
	THUASB;3 day-high	2.0883	.90048	.762	-1.1918	5.3684
	THUASB;2 day-high	7.5242(*)	.94443	.000	4.0840	10.9644
THUASB;3 day-high	MUASB;5 day-low	-8.2785(*)	1.04903	.000	-12.0997	-4.4573
	MUASB;3 day-low	-7.5711(*)	.76977	.000	-10.3751	-4.7671
	MUASB;5 day-high	-13.0529(*)	1.00677	.000	-16.7202	-9.3857
	MUASB;4 day-high	-7.4670(*)	1.04903	.000	-11.2882	-3.6458
	MUASB;3 day-high	-.5796	.92072	1.000	-3.9334	2.7742
	MUASB;2 day-high	5.2969(*)	.97263	.000	1.7540	8.8399
	TUASB;5 day-low	-.9067	1.27347	1.000	-5.5454	3.7321
	TUASB;3 day-low	-4.0742(*)	.83164	.000	-7.1035	-1.0448
	TUASB;5 day-high	-10.4329(*)	1.00677	.000	-14.1002	-6.7657
	TUASB;4 day-high	-4.0020(*)	.86772	.001	-7.1628	-.8412
	TUASB;3 day-high	4.4647(*)	.97263	.002	.9218	8.0076
	TUASB;2 day-high	11.5008(*)	1.10286	.000	7.4836	15.5181
	MHUASB;3 day-low	-8.6525(*)	1.10286	.000	-12.6698	-4.6352
	MTUASB;5 day-high	-14.2679(*)	1.00677	.000	-17.9352	-10.6007
	MHUASB;4 day-high	-10.0720(*)	.86772	.000	-13.2328	-6.9112
	MHUASB;3 day-high	-6.0856(*)	.86772	.000	-9.2464	-2.9248
	MHUASB;2 day-high	-3.0152	.94443	.176	-6.4554	.4250
	THUASB;3 day-low	13.5033(*)	1.27347	.000	8.8646	18.1421
	THUASB;5 day-high	-7.2829(*)	1.00677	.000	-10.9502	-3.6157
	THUASB;4 day-high	-2.0883	.90048	.762	-5.3684	1.1918
	THUASB;2 day-high	5.4358(*)	.94443	.000	1.9956	8.8760

Table B.1 (Continued)

(I) One way	(J) One way	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
THUASB;2 day-high	MUASB;5 day-low	-13.7143(*)	1.08699	.000	-17.6738	-9.7548
	MUASB;3 day-low	-13.0069(*)	.82075	.000	-15.9966	-10.0172
	MUASB;5 day-high	-18.4887(*)	1.04626	.000	-22.2999	-14.6776
	MUASB;4 day-high	-12.9029(*)	1.08699	.000	-16.8623	-8.9434
	MUASB;3 day-high	-6.0155(*)	.96375	.000	-9.5260	-2.5049
	MUASB;2 day-high	-.1389	1.01346	1.000	-3.8305	3.5527
	TUASB;5 day-low	-6.3425(*)	1.30492	.000	-11.0958	-1.5892
	TUASB;3 day-low	-9.5100(*)	.87904	.000	-12.7120	-6.3080
	TUASB;5 day-high	-15.8688(*)	1.04626	.000	-19.6799	-12.0576
	TUASB;4 day-high	-9.4379(*)	.91325	.000	-12.7645	-6.1112
	TUASB;3 day-high	-.9711	1.01346	1.000	-4.6627	2.7205
	TUASB;2 day-high	6.0650(*)	1.13903	.000	1.9160	10.2140
	MHUASB;3 day-low	-14.0883(*)	1.13903	.000	-18.2374	-9.9393
	MTUASB;5 day-high	-19.7038(*)	1.04626	.000	-23.5149	-15.8926
	MHUASB;4 day-high	-15.5079(*)	.91325	.000	-18.8345	-12.1812
	MHUASB;3 day-high	-11.5214(*)	.91325	.000	-14.8481	-8.1948
	MHUASB;2 day-high	-8.4510(*)	.98642	.000	-12.0442	-4.8578
	THUASB;3 day-low	8.0675(*)	1.30492	.000	3.3142	12.8208
	THUASB;5 day-high	-12.7188(*)	1.04626	.000	-16.5299	-8.9076
	THUASB;4 day-high	-7.5242(*)	.94443	.000	-10.9644	-4.0840
	THUASB;3 day-high	-5.4358(*)	.94443	.000	-8.8760	-1.9956

B.2 Two ways ANOVA for COD concentration

From the two-way ANOVA result, it found that there was a significant effect of reactor type, HRT, and temperature, so it implied that the mean of COD removal varied between the HRT of five, four, three, and two days and the temperature of mesophilic and thermophilic. In addition, there was statistical indication of interaction between HRT and the type of reactor, thus the effect of HRT on the COD removal varied significantly with the variation of reactor. The COD removal differed due to the effect between HRT with temperature and reactor with temperature. The two-way ANOVA result showed the COD removal varied with the effect of three variable operation conditions.

Table B.2 Two-way ANOVA Test of between subject effects with COD removal as dependent variable

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8557.152(a)	21	407.483	83.755	.000
Intercept	1154941.707	1	1154941.707	237389.860	.000
REACTOR	19.691	1	19.691	4.047	.046
TEMP	2433.521	1	2433.521	500.193	.000
HRT	4944.458	5	988.892	203.259	.000
REACTOR * TEMP	428.646	1	428.646	88.105	.000
REACTOR * HRT	1199.891	4	299.973	61.657	.000
TEMP * HRT	360.665	5	72.133	14.826	.000
REACTOR * TEMP * HRT	419.805	4	104.951	21.572	.000
Error	982.764	202	4.865		
Total	1566581.381	224			
Corrected Total	9539.916	223			

a R Squared = .897 (Adjusted R Squared = .886)

APPENDIX C PHOTOS

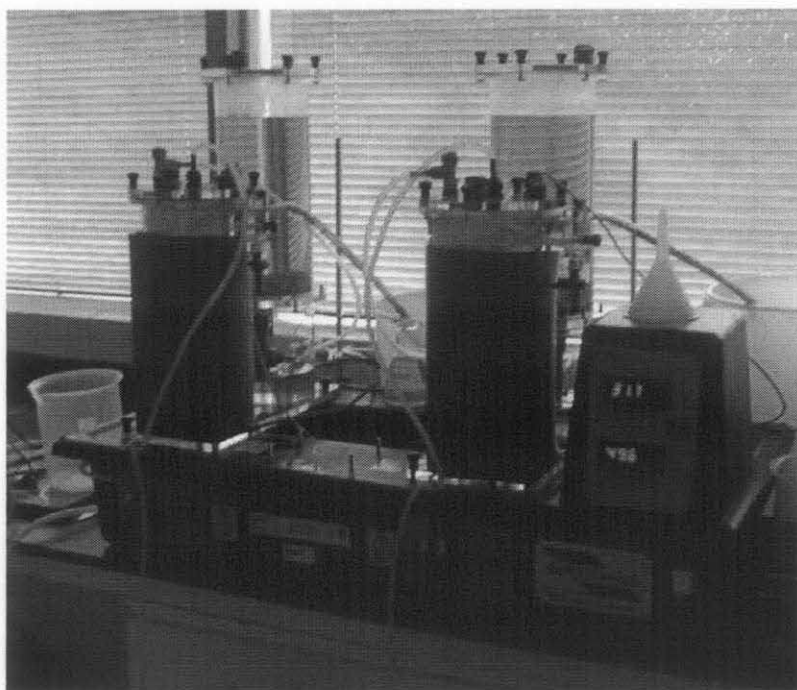


Figure C.1 Anaerobic reactors (Armfield Anaerobic Digester W8)

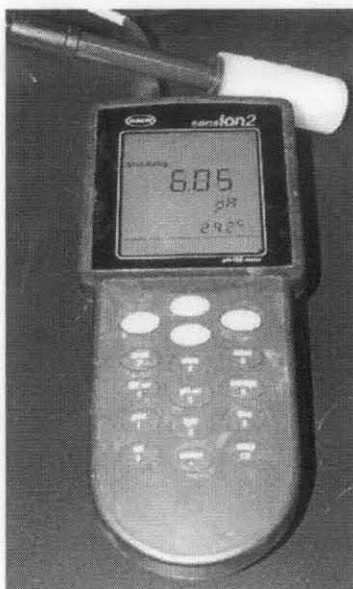


Figure C.2 Hach pH meter (Model Sension 4) using Platinum Series pH Electrode
(Model 51910)

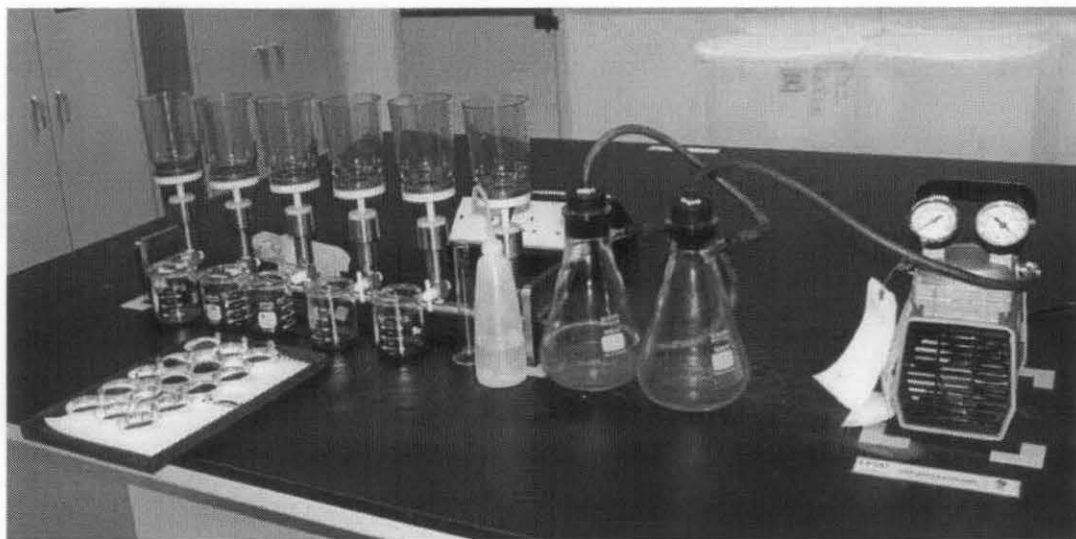


Figure C.3 Solids measurement apparatus



Figure C.4 Analytical balance (Mettler Toledo AB204-S)



Figure C.5 Muffle furnace (Nabertherm L15/12/P320)

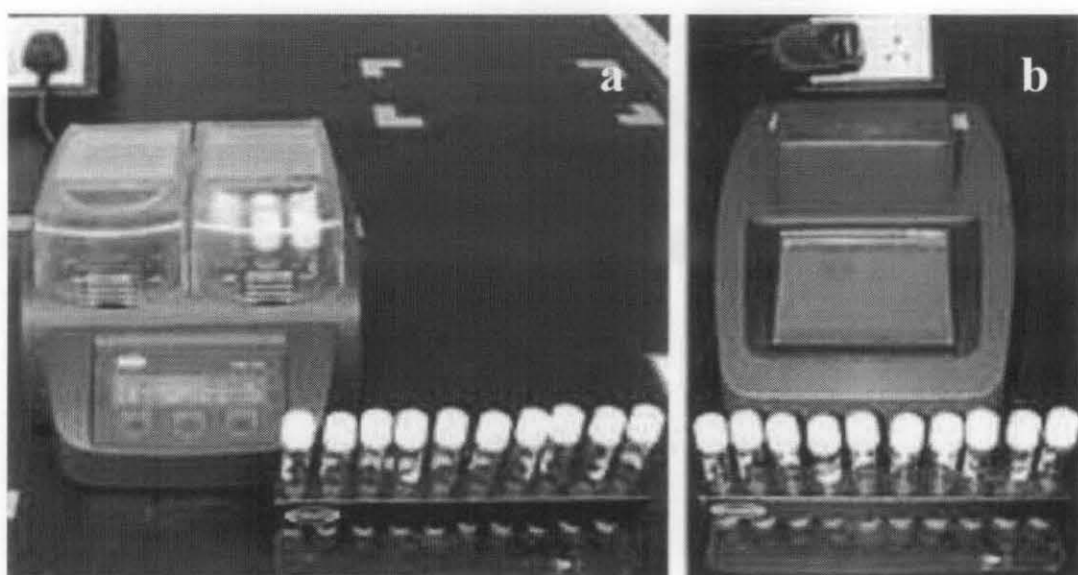


Figure C.6 (a) Hach digestion reactor, (b) Hach spectrophotometer DR 2000 and high range COD digestion reagent vials

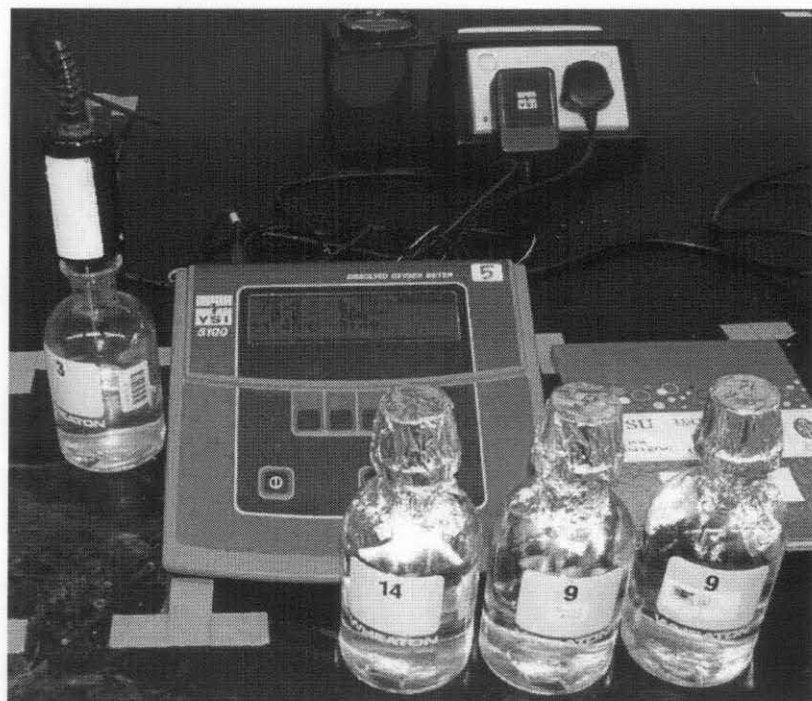


Figure C.7 YSI 5100 Dissolved Oxygen Meter

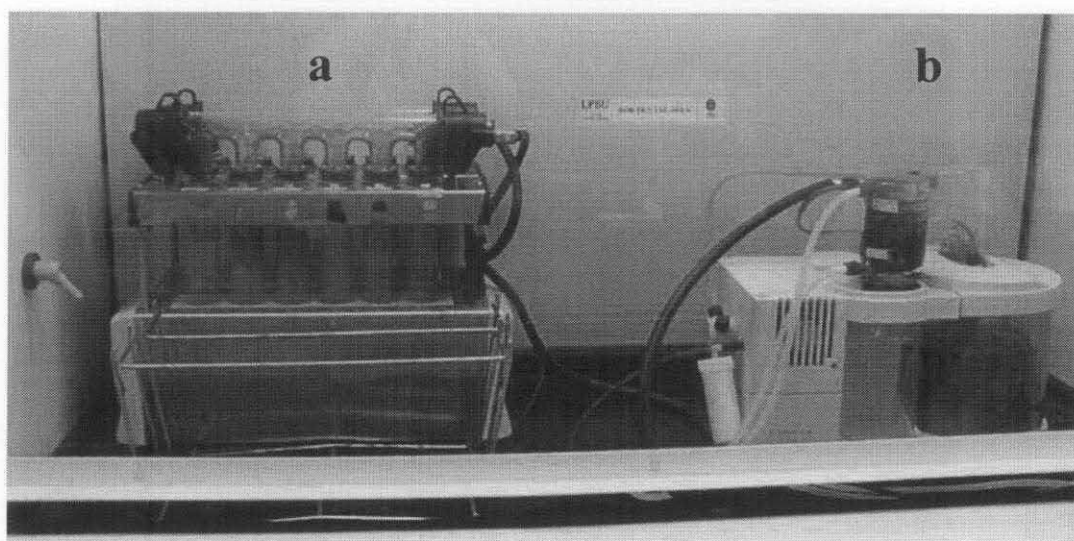


Figure C.8 (a) Buchi K-424 Digestion Unit and (b) Buchi B-414 Scrubber Unit



Figure C.9 Buchi K-314 Distillation Unit

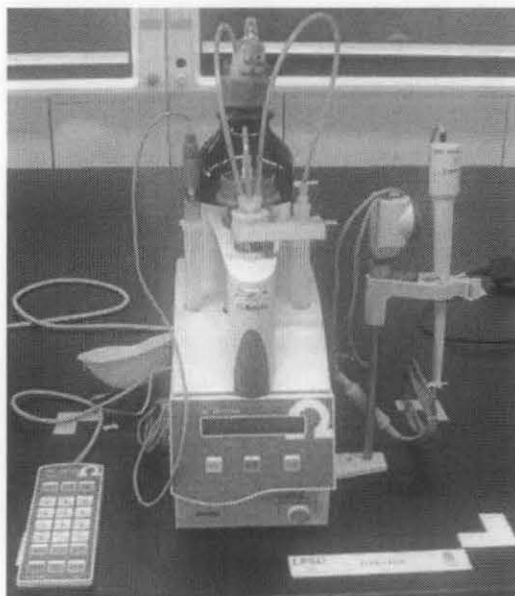


Figure C.10 Auto titration unit (Metrohm 702 SM Titrino)



Figure C.11 Seed biomass from sludge thickener

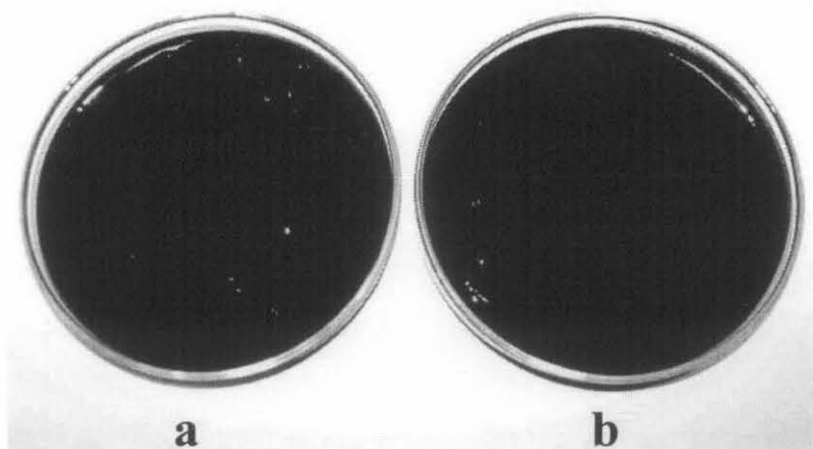


Figure C.12 (a) Mesophilic UASB sludge and (b) thermophilic UASB sludge

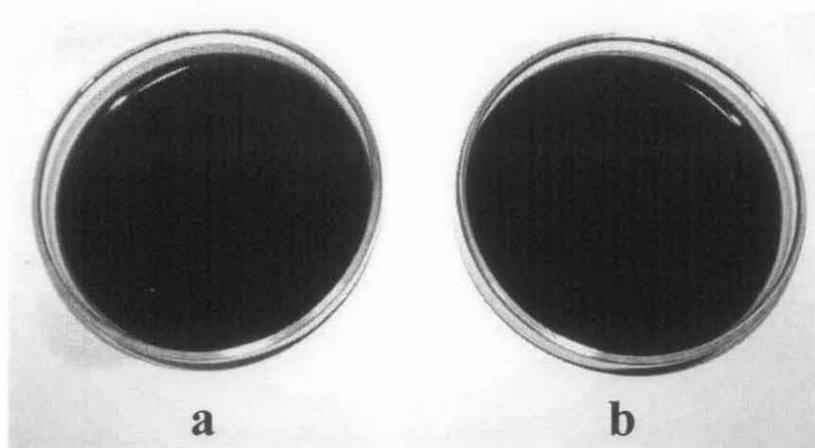


Figure C.13 (a) Mesophilic HUASB sludge and (b) thermophilic HUASB sludge

VITAE

The author of this thesis, Welly Herumurti, was born on December 23rd, 1981, in Malang, province of East Java, Indonesia. He started his bachelor degree (Sarjana Teknik/ST.) in Department of Environmental Engineering in 2000 at Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia and he obtained his degree in 2005. His final year project report was on the nutrient removal of sewage wastewater using sub-surface (SSF) constructed wetlands. He was appointed as staff at Department of Environmental Engineering ITS Surabaya in 2006. His master degree was started officially in 2007 at the Department of Civil Engineering Universiti Teknologi PETRONAS (UTP) Malaysia. He obtained allowance under Graduate Assistantship (GA) scheme to do a Master of Science (M.Sc.) in Civil Engineering, specialization Environmental Engineering in UTP Malaysia.

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